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HELICOPTER DEVELOPMENT RELIABILITY TEST REQUIREMENTS

VOLUME I

STUDY RESULTS

By

K. G. Rummel

April 1971

EUSTIS DIRECTORATE

U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY

FORT EUSTIS, VIRGINIA

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THE BOEING COMPANY, VERTOL DIVISION
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13. ABSTRACT

This report covers a study to identify optimum reliability problem identification and demonstration test concepts for helicopter dynamic components, in order to facilitate formulation of cost-effective reliability test programs for future helicopters. Detailed failure mode test technique problem identification capability and cost data are presented from CH-47 helicopter development experience to aid in calculating specific test costs for future development programs. Sample test plans are presented for two helicopters representing size extremes. A plan is outlined for revising selected existing design and test Military specifications and supplementing them with additional handbooks and specifications.

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DEPARTMENT OF THE ARMY
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This report, Volume I of a three-volume report, was prepared by the Boeing Company, Vertol Division under the terms of Contract DAAJ02-70-C-0039. It presents the results of a study to establish the relationships between various reliability demonstration objectives and the test requirements (type, hours, components required, cost, etc.) necessary to achieve those objectives.

The objective of this contractual effort was to perform historical data review and analysis and cost and effectiveness trade-offs necessary to identify reliability testing requirements that are applicable during new helicopter system development programs.

In general, it can be stated that the helicopter development reliability test programs presented in this report are a possible approach to a helicopter dynamic components development effort.

In Volume II, use of probabilities and statistics to define demonstration requirements in order to predict reliability is discussed. and selected assumptions, terminology, and variables used in the basic report are explained and their interrelationships clarified.

Volume III will further explore the relationship between test costs and quantitative reliability requirements. It will also examine the sensitivity of the cost/reliability relationship to those variables whose specific values were selected through engineering judgements for two purposes:

a. To allow the Government to evaluate the tolerance of the cost outputs to the input assumptions.

b. To identify areas that can profoundly influence the test cost/reliability relationship, thus flagging them for a high degree of consideration and control by the Government and the contractors.

The conclusions and recommendations contained herein are concurred in by this Directorate. The concurrence is based on acceptance of the data reviewed and assumptions made in performing the analysis and trade-off studies leading to the development of the sample test plans.

The technical monitor for this contract was Mr. Thomas E. Condon of the Reliability and Maintainability Division of this Directorate.

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HELICOPTER DEVELOPMENT RELIABILITY TEST REQUIREMENTS

VOLUME I

STUDY RESULTS

Final Report

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Details of illustrations in
this document may be better
studied on microfiche

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SUMMARY

This report presents the results of a study that explores the relationship between quantitative reliability requirements imposed on helicopter major dynamic components and the development test programs and associated expenditures necessary to achieve these requirements.

The study is performed to facilitate formulation of cost-effective reliability test programs for future helicopters having contractual numerical reliability requirements. To this end, the study identifies and documents the independent decisions and resulting dependencies that affect the costs of reliability testing. Further, detailed failure mode, test technique problem identification capability, and cost data elements are presented from Boeing's CH-47 helicopter development experience, to aid in calculating specific test costs for future developmental programs. Sample test plans are presented for two helicopters, representing extremes of size, weight and complexity.

The basic axioms which establish the course of the study are:

1. Reliability requirements that must be contractually demonstrated at a specified confidence level in a relatively short demonstration test, in turn, result in a requirement for contractors to develop products with a still higher actual reliability, the level of which is also a function of the desired probability of passing the demonstration.

2. Achievement of this higher actual reliability results from the effects of initial design attention and aggressive testing to identify and eliminate reliability problems. The degree of testing and, consequently, test costs vary with the higher level of actual reliability required.

3. Historical test experience can be used to evaluate potential future test effectiveness, through which optimum approaches can be formulated.

The conclusions of the study indicate that within reasonable limits, reliability-oriented test costs are more significantly influenced by the demonstration concept selected, the absolute values of reliability to be demonstrated, and the associated demonstration confidence level, than by the elapsed time permitted for reliability development, or the particular mix of reliability test techniques selected. Further, pre-implementation of development testing of critical dynamic components is advantageous from the total life cycle cost

viewpoint, and, in many cases, can also result in a reduction in development test costs. Finally, total development test costs are greatly influenced by safety and performance considerations, with significant cost segments being independent of the numerical reliability levels required.

Reliability test costs are sensitive to both program decisions and management attitude, and application of the analytical approaches of this study to future reliability test program planning can result in significant savings. It is recommended that optimization of nonreliability oriented testing be studied in terms of its unique test objectives. It is also recommended that the relationships between the reliability requirements selected for a product and the resulting total product life cycle cost be explored, to permit the selection of the appropriate numerical value in order to achieve minimum life cycle costs.

Finally, a plan is outlined for revising selected existing design and test Military specifications and supplementing them with additional handbooks and specifications. The aim of this revision is the creation of planned integrated documentation establishing the general framework for specifying reliability requirements and establishing appropriate reliability program identification and demonstration test plans.

FOREWORD

This report covers a study to identify optimum reliability problem identification and demonstration test concepts for helicopter dynamic components, conducted under Contract DAAJ02-70-C-0039 for the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory (USAAMRDL), Fort Eustis, Virginia.

AMRDL technical direction was provided by Mr. T. House and Mr. T. Condon. The Contracting Officer was Mr. W. Oyler.

The principal investigator for The Boeing Company, Vertol Division, was Mr. K. G. Rummel of Reliability Engineering, who was assisted by Mr. J. W. Woolman of the Engineering Laboratories; Messrs. A. Spiegel, R. Jines, and C. Burdan of Reliability Engineering; and Mr. F. Sauter of Value Engineering. Program management and technical direction were provided by Mr. G. W. Windolph, Manager, Product Assurance Technical Staff, and Mr. R. B. Aronson, Unit Chief, Reliability Engineering.

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LIST OF ABBREVIATIONS AND SYMBOLS

"A" (helicopter)	15,000-pound gross weight single-rotor shaft-driven helicopter
"B" (helicopter)	90,000-pound gross weight tandem-rotor shaft-driven helicopter
demo-in	Demonstration early in the development cycle supported by development funds
demo-out	Demonstration on operational aircraft in the field
DST	Dynamic systems test
IROAN	Inspect and repair only as necessary
MTBF	Mean time between failures
MTBR	Mean time between removal
MTBR*	Mean time between removal to be demonstrated
Required MTBR	Mean time between removal resulting from problem identification (PI) test, and required to pass demonstration test
MTBUR	Mean time between unscheduled removals
PI	Problem identification
TBO	Time between overhaul

Test Detection Symbols

●	Problem was actually detected during test technique
⊕	Problem could have been detected except for the presence of artificial restraints
O	Problem could have been detected if test had been operated for sufficient duration
X	Problem cannot be detected because of inherent restraints

1. INTRODUCTION

Helicopters have traditionally exhibited higher unscheduled maintenance requirements than fixed-wing aircraft of comparable size (Figure 1) because of the greater percentage of high-reliability-risk and high-cost components needed for the helicopter's unique performance capabilities. This, in turn, is reflected in the distribution of maintenance costs, where most of the costs are contributed by these same high-cost, relatively low-reliability components (Figure 2).

These components are the major units of the drive and rotor systems, and upper flight controls. Since their nature causes them to be relatively expensive, maximum reliability and long service life become paramount objectives.

While both contractor and customer recognize the need for improved reliability and service life, achieving this without a long period of expensive "product improvement" has been infrequent. Equally important is the fact that the relationship between developmental effort and high initial reliability is generally unknown. This study provides quantification of the developmental test portion of this relationship.

Inherent hardware reliability is a function of two activities. The first is the analytical process through which a component is designed. This process includes basic sizing, selection of design allowables, detail drawing, design review, prediction of reliability levels, and other activities and considerations developed to produce an acceptable configuration as it comes "off the board". The second activity is empirical in nature, involving the actual testing of the design to confirm and improve its performance. Most programs employ these two activities in combination, with the emphasis varying from vehicle to vehicle and from time to time.

Of these two methods, the first (analytical) holds more long-range potential for cost-effectively producing higher levels of reliability. However, with the technology currently available for the next generation of helicopters, extensive emphasis will necessarily be applied in the testing area to meet reliability goals.

Before this emphasis can be applied effectively, many questions must be answered concerning the relationships between developmental test costs, schedules, mixes of techniques, and reliability benefits.

The need for understanding has been succinctly stated:

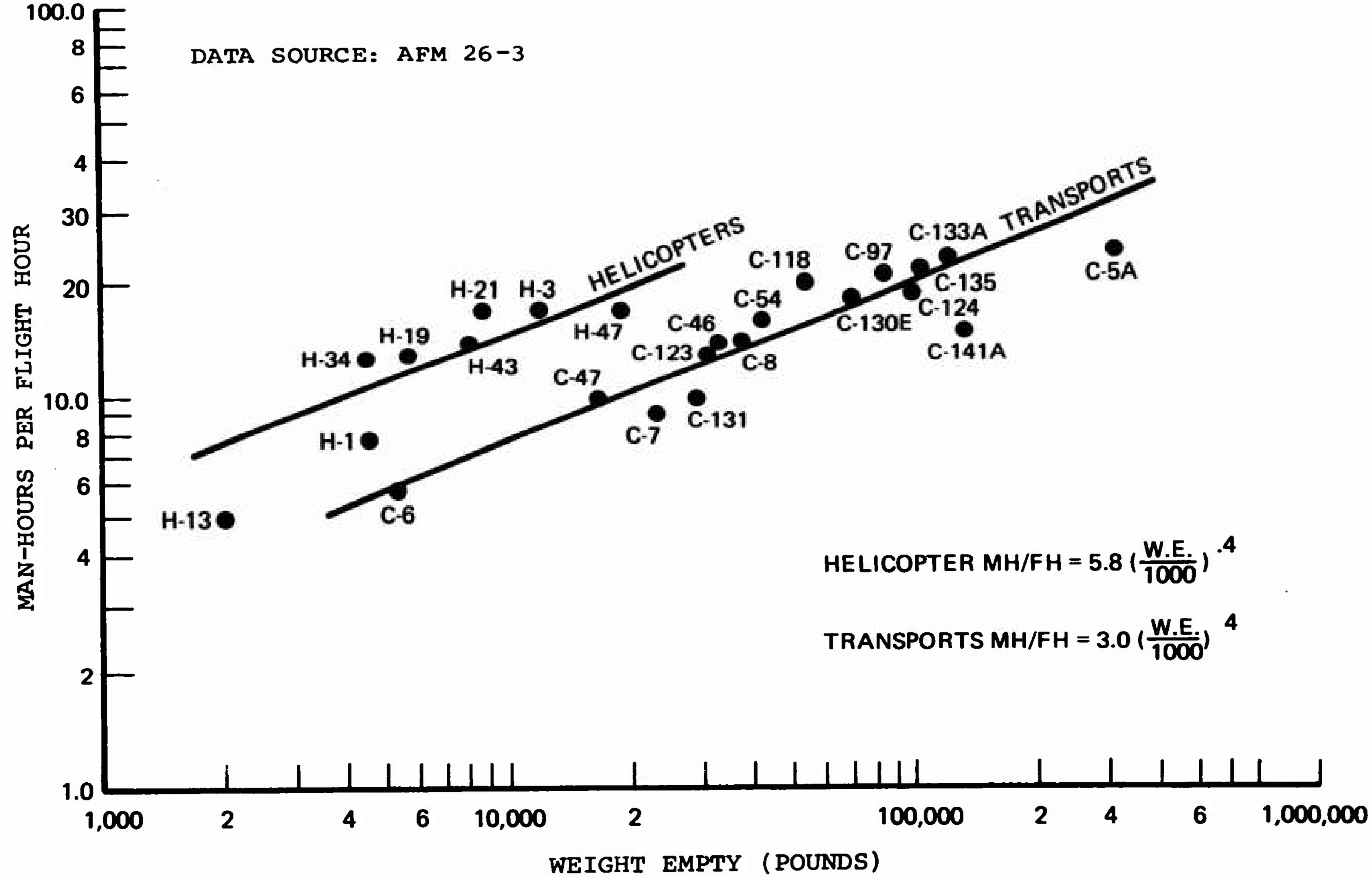


Figure 1. U.S. Air Force Helicopter and Transport Maintenance.

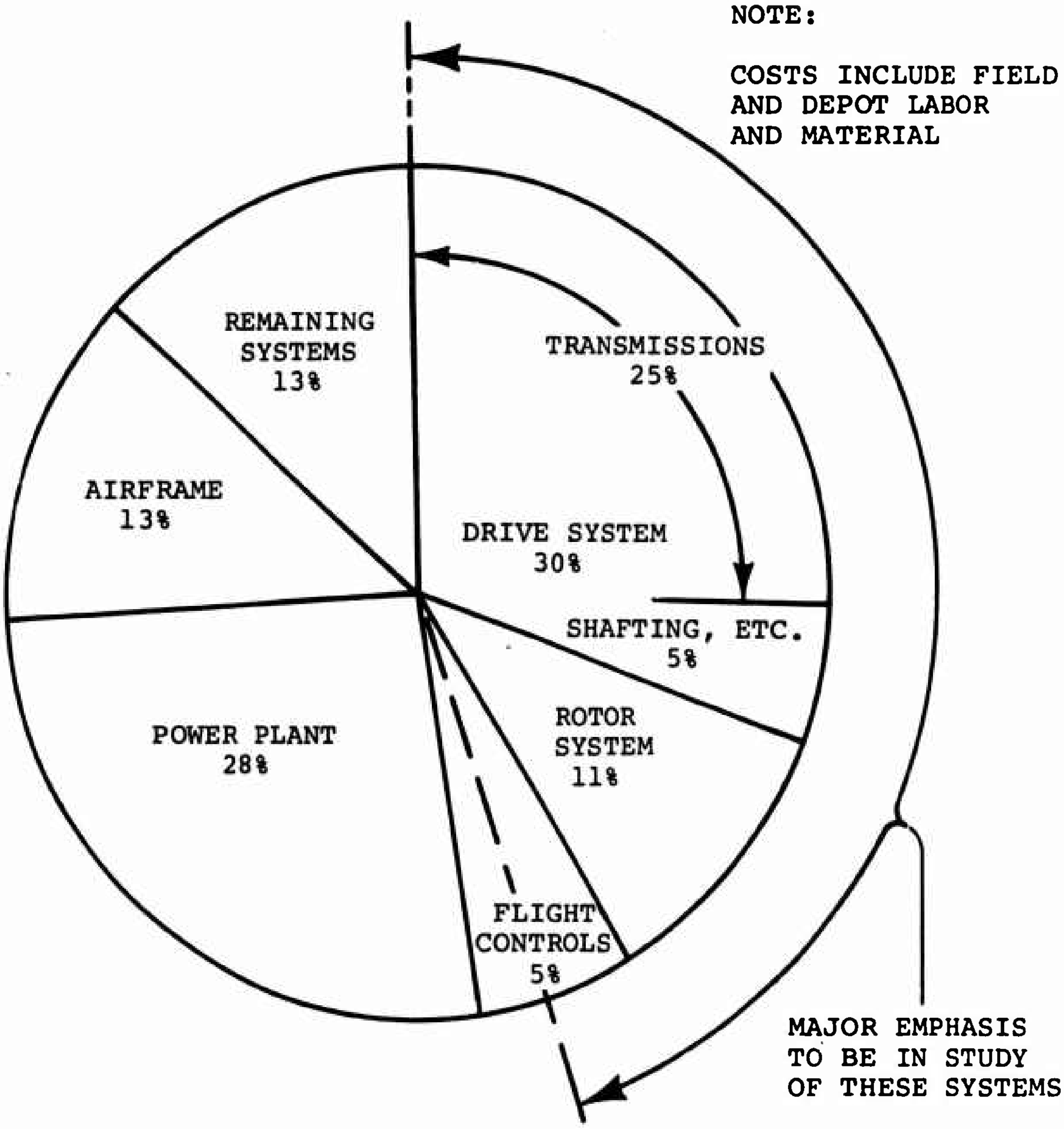


Figure 2. Analysis of CH-47A Direct Maintenance Costs.

"In spite of the increasing impact of testing on cost, we have not progressed very far in developing a capability to optimize a test program in terms of cost effectiveness. However, the need has been recognized and attempts have been made to improve test effectiveness through the use of integrated test planning. By integrated, we mean a plan which rationalizes the overall test philosophy to the unique characteristics of the end product and which relates test criteria, environments, duration and sequence in a way which enhances the overall cost effectiveness of the test program." (Reference 1)

Moreover, the growing requirement for reliability demonstration must be considered. The type, duration, and phasing of demonstration must be considered, in conjunction with the developmental testing.

This study investigates the impact of variations in the following parameters on development test costs:

1. The mix of test techniques
2. The type and placement of the demonstration
3. The duration of the demonstration
4. The MTBR and confidence level desired
5. The elapsed time of the developmental and demonstration program
6. The size, weight, and configuration of the aircraft

The baseline data for this study was obtained from historical test and service experience of the CH-47A, B, and C helicopters in the areas of test technique detection potential, test schedules, costs, and detailed failure modes and rates.

Candidate test programs for a 15,000-pound gross weight shaft-driven helicopter were arranged consisting of various mixes of test techniques occurring over varying time periods, achieving varying MTBR's, and with varying demonstration durations. The candidate test programs were used to display the cost sensitivities of the parameters discussed above.

Based on this analysis, recommended test plans for a 15,000-pound gross weight single-rotor shaft-driven helicopter (hereafter called Helicopter "A") and a 90,000-pound gross weight tandem-rotor shaft-driven helicopter (hereafter called Helicopter "B") were prepared with accompanying costs and schedules.

Existing specifications relating to test requirements were also reviewed and appropriate recommendations were made.

The study was designed to explore the sensitivity of test costs to the many decisions that are made during the natural course of a development program. The results of the study will assist in making decisions in current and future programs.

A wide spectrum of administrative and technical personnel participate (consciously or not) in the creation of these costs. An important result of this study will be the resulting awareness of the impact of their activities on test costs.

2. SCOPE

DEFINITION OF TEST TYPES AND OBJECTIVES

As the first step of the analysis, the several specific objectives of test must be recognized. Review of past test programs suggests that specialized objectives have created five unique types of reliability tests:

Type I	General design development (analytical methods confirmation)
Type II	Reliability problem identification
Type III	Reliability problem investigation
Type IV	Reliability demonstration
Type V	Production quality assurance

It is important that these classifications be understood, since they provide the framework for establishing the scope of this study. A general description of each classification follows.

Type I: General Design Development

These tests occur early in the program and are supported with developmental funds. They support design by aiding material and configuration selection and component sizing. Both ground and flight tests are involved. Component fatigue strength tests dominate the ground tests. These tests identify the strength capability of a particular design through the establishment of load versus life relationships (commonly known as S/N curves). Other ground tests include coupon tests, grease/oil evaluations, photoelastic studies, strain and vibration surveys, and spring rate determinations.

The important characteristic that these tests share is the nature of their output. Since they have narrow, specialized objectives, the loads and/or conditions, configuration, and test criteria are optimized to rapidly answer those specific objectives, thus precluding determination of overall component reliability. For example, a fatigue test of a rotor component such as a pitch housing is usually performed with the loads being reacted through a rigid mounting system. Since no component movement is involved, potential field reliability problems involving pitch housing bearing spalling or seal leakage are not produced or detected.

Certain portions of flight testing which are not directly related to reliability problem identification are also included in Type I. These include structural demonstration, stress and motion surveys, and performance surveys. This optimization of test technique selection to fulfill specific objectives that are either unrelated to reliability or that

address only a single failure mode distinguishes Type I tests from Type II tests.

Type II: Reliability Problem Identification

These tests also occur early in the development of a helicopter and are also supported with developmental funds. Their objective is to determine the existence, rate, and cause of reliability problems and determine if corrective action is necessary and effective. This type of test, sometimes referred to as an endurance, qualification, or service test, is performed at the detailed component, assembly, and completed-aircraft levels.

Examples of tests in this category include transmission bench endurance, rotor whirl tower, rotor hinge bearing endurance, tiedown, and dynamic systems tests. These ground tests are designed to simulate the actual loads and conditions experienced on the aircraft. Flight testing is also included in this category when designed to identify reliability problems.

The common element of Type II tests is that they are constructed to maximize the identification of all potential failure modes. The extent of Type II testing performed should be determined by the severity of the reliability requirements.

Type III: Reliability Problem Investigation

This type of test is performed later in the development phase and runs well into the production phase of a helicopter. Type III tests are usually funded out of production or sustaining funds. They are designed to understand field-identified problems. Resolution of a problem requires knowledge of the causes and mechanism of failure, duplication of the failure under controlled test conditions, and verification of the effectiveness of the fix under similar test conditions. Type III tests are of special interest in this study because they have been specifically designed to reproduce certain failure modes that have gone undetected in past tests. As such, they serve as a pool of new test techniques for considerations as Type II tests in future programs.

Type IV: Reliability Demonstration

The timing and funding source for these tests are not as definite as for Type I, II, and III. Demonstration tests may be performed at any customer/contractor agreed-upon point where the hardware is available for test. This could be immediately after completion of Type II tests or well into the production phase when a quantity of aircraft is available. Correspondingly, the funding source would be developmental if the demonstration was early and required operation of the equip-

ment solely for demonstration purposes. Alternately, a demonstration could be held later in the procurement cycle, after a "buy" decision had been made. Then, production hardware would be operating; operational costs would be paid for with O&M funds; and development funds would provide only acquisition and analysis.

The objective of Type IV demonstration testing is to prove to the customer that contractual reliability requirements have been met, not to detect reliability problems. Demonstration tests require several important characteristics:

1. A constant configuration

2. Test conditions that realistically represent combat-theater environment operational usage of the hardware, along with proper interface conditions

3. Adequate duration

These factors suggest that flight vehicles in the field are the most suitable method of reliability demonstration and that demonstration should be performed only after the design configuration has been stabilized. Changing configurations, extreme loads or conditions, or inadequate duration tend to degrade the usefulness of test results for statistical treatment and demonstration purposes.

Type V: Production Quality Assurance

This is testing to determine if a prior numerical value of reliability is being maintained throughout the production of the hardware. Supported by production-type funds, these tests are clearly not developmental.

DEVELOPMENT ORIENTED TEST TYPES

This study is to determine the effect on development costs of various reliability requirements; consequently, only Type I, II, and IV tests were considered from a cost and effectiveness standpoint. Type III tests were reviewed as a source for new Type II test techniques, but were not costed or traded since they do not use development funds. A discussion of the analytical scope of each test type follows.

Type I (Design Development)

The sole purpose of Type I tests is to confirm that the basic design approach and initial sizing of components are acceptable. Therefore, the analysis of these tests must be handled in a different manner than the Type II tests.

Fatigue tests confirm that the components, as designed, are acceptable for flight testing from a basic strength standpoint. Most helicopter failure modes which could cause an unsafe condition or result in massive program delays are related to the strength of the components in the major dynamic systems. Consequently, helicopter test programs have historically been oriented toward early verification that the basic design is adequate from a minimum safety standpoint; and have then progressed to tests which improve reliability, TBO intervals, unscheduled removals, maintenance, etc. This requirement for optimization of Type I testing to provide early strength verification essentially precludes determination and improvement of overall component reliability. Therefore, the amount of testing that is performed in this category is dependent less upon specific quantitative reliability objectives for the aircraft/component than upon the following factors:

1. Level of technology in materials/design used

2. Confidence or uncertainty in basic sizing methodology

3. Size, weight, and configuration of aircraft

4. Level of safety desired or program risk that can be tolerated

For these reasons, this study does not quantitatively measure the effectiveness of Type I tests. Type I tests were sized considering appropriate levels for the factors listed above, and were not varied as a function of numerical reliability requirements. Type I tests are discussed in terms of their costs, problem identification capability, and appropriate improvements for future programs.

<u>Type II (Reliability Problem Identification)</u>

The effort expended on tests in this category is directly related to the numerical reliability levels desired. This study explored how the costs of these tests vary as a function of reliability levels, the mix of specific test techniques, and the elapsed time allowed for the program.

The study quantified the effect on program costs of these variables for Helicopter "A" by creating and evaluating candidate test programs. These programs consisted of combinations of test techniques consuming varying amounts of elapsed time and yielding various levels of reliability.

Type IV (Demonstration)

In this study, only flight test demonstrations were considered acceptable, both to assure correct loads and environments and to assure realistic interfaces.

Under this ground rule, demonstration costs are a function of only two variables:

1. Demonstration duration

2. The scope of the effort bought with developmental funds

The effect of variations in demonstration duration on total cost was determined. Also, two different demonstration concepts were evaluated. The first concept involved demonstration prior to a "buy" decision, i.e., before initiation of production for service use. Here, the total cost operation, maintenance, data collection, and analysis for the demonstration were charged against developmental funds. The second demonstration concept evaluated involved demonstration using production aircraft operating routinely in the field. Here, the only demonstration costs incurred against developmental funds consist of the cost of data collection and analysis.

THE MTBR PARAMETER

Many parameters can be used to describe the reliability characteristics of aircraft systems and components. They range from expressions of "downtime due to maintenance" to "mission reliability". The most meaningful parameter from a life cycle cost standpoint is mean time between removals (MTBR). This parameter reflects the largest segment of life cycle costs (i.e., depot overhaul and repair), since the Army does not have extensive field or shop level facilities. For this reason, MTBR was chosen to be the sole unit of measurement in this study.

MTBR reflects both scheduled and unscheduled removals. Typically, the bulk of scheduled removals are for TBO reasons. Unscheduled removals include failures or suspected failure and removals due to combat damage. Removals to facilitate maintenance of other components are not included in the parameter. Unscheduled removals due to combat damage were excluded from this study.

The philosophy of time scheduled replacement (TBO) of dynamic components has been the subject of extensive analysis in the last few years. Current technology is being directed at incorporation of diagnostic equipment, which, when coupled with the appropriate design concepts, will eliminate the requirement for scheduled TBO removals. For this study, an

"on-condition" maintenance philosophy has been assumed; hence, all removals constitute unscheduled removals, and the parameter MTBR is identical to MTBUR (mean time between unscheduled removals).

3. STUDY APPROACH (BASED ON HARDWARE RELIABILITY DEVELOPMENT CYCLE)

HARDWARE DEVELOPMENT PROCESS

The hardware development process and the effect of numerical reliability requirements on the costs of reliability problem identification and demonstration testing can best be understood by examining the MTBR flow chart (Figure 3). As shown on the flow chart, the design and analysis activity produces components with initial reliabilities identified as "MTBR off the board". These components are then subjected to reliability problem identification testing to identify, correct, and verify correction of reliability problems. This effort continues until a level of hardware reliability is reached of sufficient magnitude to provide reasonable assurance that a formal demonstration test will be successfully completed. Subsequent completion of the demonstration provides assurance that the contractual reliability requirement has been satisfied at the required level of confidence.

Four factors ultimately determine the costs of reliability tests:

1. The input: MTBR off the board
2. The output: MTBR required out of reliability problem identification (Type II) tests
3. The cost and effectiveness of Type II testing in improving the MTBR
4. The demonstration test costs (Type IV)

There is, therefore, an interrelationship among problem identification test costs, demonstration test costs, and the numerical reliability requirement. Analytical confirmation tests are relatively independent of numerical reliability requirements.

STUDY APPROACH

The study approach is compatible with this hardware development process and is designed to evaluate and optimize problem identification and the resultant demonstration. Figure 4 illustrates this approach.

The first step in this approach is the use of historical CH-47 data to evaluate test techniques in terms of problem identification capability, cost, and elapsed time restraints. The next step is the construction of candidate test programs that collectively evaluate all of the applicable aircraft dynamic

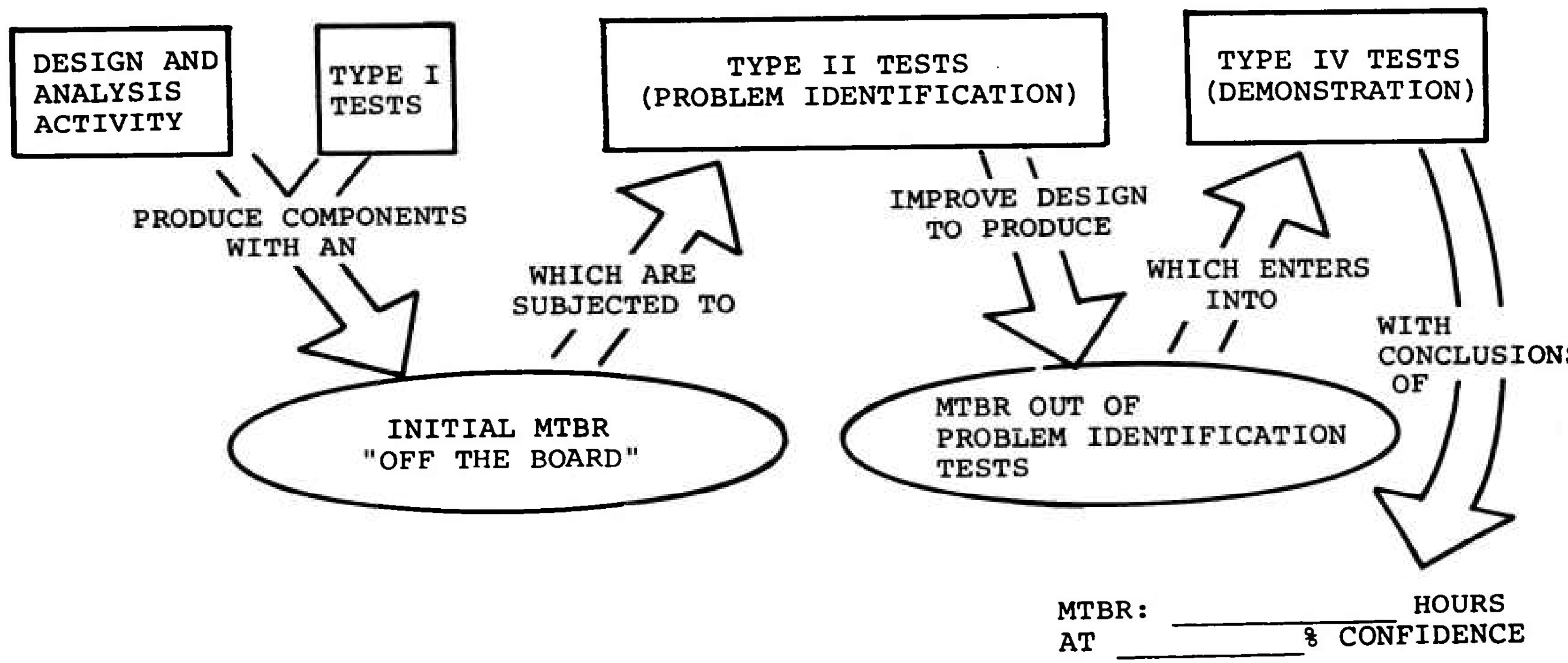


Figure 3. Growth of Component Reliability Through Design and Test.

components, consisting of various mixes of test techniques requiring various elapsed times, over a range of MTBR. These various programs define the trade-offs which allow evaluation of alternate mixes of test techniques and the effect of various elapsed times and MTBR on test costs.

Demonstration tests are then constructed to demonstrate specific MTBR values (500, 1,000, and 1,500 hours) at confidence levels of 30, 60, and 90 percent. The problem identification and demonstration test costs are added to produce totals. In addition, other tests which are independent of reliability requirements are costed and added to the previous totals.

Sample plans are constructed for helicopters of extreme differences in size, weight, and configuration; these plans are costed accordingly.

As a final task, selected specifications are reviewed to identify any areas contained therein that conflict with the results of the study.

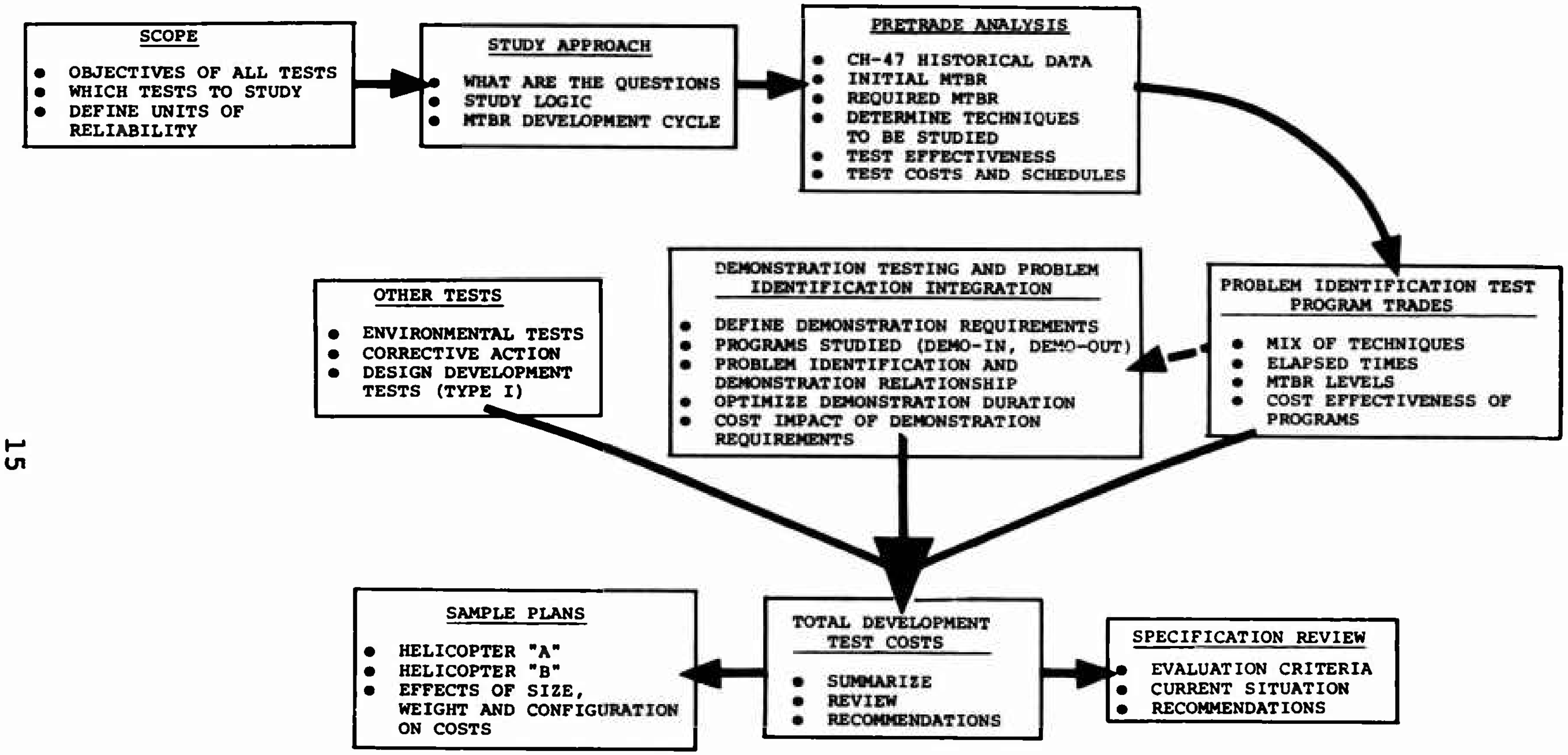


Figure 4. Program Activity Flow Diagram.

4. PRETRADE ANALYSES AND OBSERVATIONS

DETERMINING THE RELIABILITY OFF THE BOARD

Determining the reliability characteristics of the components as they enter test involves a necessarily subjective consideration of the contractor's state-of-the-art ability to produce designs free of problems. This state of the art varies from component to component, from year to year, and from contractor to contractor. The off-the-board estimates made in this study reflect the individual component's design (size, weight, configuration, loads, etc.) and the specific time at which the design would occur. The estimates reflect the experience of one contractor, with a specific level of effort expended on initial design.

Specifically, off-the-board estimates were made for the dynamic components of Helicopter "A". The estimates consisted of predicted failure modes and their failure rates (MTBF) existing in each of the major dynamic components before any Problem Identification tests are begun.

In predicting the off-the-board failure modes, the following procedure was used: all available problems experienced with the major dynamic components on the CH-47A, B, and C models were collected and analyzed. The CH-47 components reviewed are shown in Appendix I. These sources included detailed and summary reports of failures which occurred in both field operational use and testing. All failures that caused unscheduled removals or high maintenance, or that had potential impact on flight safety, were tabulated. Of over 700 problems recorded, 254 separate problems (failure modes) were selected as being "significant". Significant was defined to include:

1. All potential safety-affecting modes

2. Modes causing unscheduled removals that occurred more than twice in the history of the CH-47

3. Modes that caused recognizable maintenance man-hour expenditures at either the field or depot level

4. All problems that occurred in test which would cause an unscheduled component removal

For these 254 significant problems, additional data were gathered concerning the cause, impact, and rate of failure. This information and the degree to which the detection of these problems occurred in test are displayed on a matrix (see Appendix II).

These data were then used as the baseline for the Helicopter "A" off-the-board unscheduled removal rate predictions. The predictions were for a configuration that had been developed by Boeing-Vertol with similar specifications as Helicopter "A". The detailed procedure for modifying the CH-47 baseline experience for the Helicopter "A" design was as follows:

1. Unscheduled removals caused by failure modes that appear to be susceptible to control (elimination) by design practices or procedures were eliminated. Examples are removals caused by transmission lock-nuts backing off, bearing outer races spinning, etc.

2. Unscheduled removals caused by failure modes which are still present, but where new design features have been incorporated to facilitate repair without the need to remove the parent assembly, were also eliminated. Examples of this are rotor blade tip cover failures, sprag clutch failures, etc.

3. Where certain Type I tests are added to the Helicopter "A" test program for the purpose of eliminating specific failure modes, these modes are eliminated from the off-the-board prediction. Examples of these modes are rotor blade erosion, torsional fatigue cracking of drive shaft adapters, etc.

4. Where the specific design incorporated concepts or materials not utilized on the CH-47, failure modes causing removals were added. Examples are super-critical-speed drive shafts, rigid main rotors, etc.

These predictions consider detailed failure modes that could cause an unscheduled removal of the components on Helicopter "A" and their rates. These modes are the total number of problems which exist in the components as they are initially designed and that need to be detected and corrected during the Type II (problem identification) test program.

NOTE

It is emphasized that the off-the-board predictions are appropriate only to a specific size and configuration aircraft and reflect the extent of the analytical process and Type I tests that support the design.

It should be understood that, in terms of the ultimate effect upon test duration (costs), the distribution of the individual component failure mode frequencies is more important than the absolute value of the total assembly MTBR.

DETERMINATION OF RELIABILITY REQUIRED TO PASS THE DEMONSTRATION (OUTPUT OF PROBLEM IDENTIFICATION TESTING)

The component MTBR that must be produced by a Type II test program is a function of four variables, all relating to the subsequent demonstration:

1. The MTBR to be demonstrated (hereafter shown as MTBR*)

2. The confidence level at which the MTBR* must be demonstrated

3. The desired probability of hardware passing the demonstration

4. The duration of the demonstration

As the MTBR* or the confidence level increases, the MTBR that must be produced by the Type II test (hereafter described as the required MTBR) must also increase.

The effects upon the required MTBR of changes in the desired probability of passing the demonstration or in the demonstration duration are frequently unrecognized. Regardless of how excellent its actual reliability may be, it is less than a certainty (i.e., less than a 100 percent probability) that a given component will pass a given reliability demonstration. Nevertheless, the probability of passing a defined demonstration increases as the equipment's actual reliability increases. For this reason, the required MTBR increases as the desired probability of passing increases for given levels of MTBR* and confidence in a defined demonstration. In respect to duration, demonstration tests attempt to define the true reliability of a population of components by observing a small sample of the population for a finite period of operation. The longer a demonstration test runs, the more closely the true MTBR of the population will be approximated by the actual test results from the sample. For this reason, demonstration tests are constructed so that higher required MTBR's are necessary to offset the risks associated with short-duration demonstrations. The result is that in demonstrating a specific MTBR* at a specific confidence level, the required MTBR will <u>decrease</u> as the demonstration test becomes longer.

As specified in the Statement of Work for this study effort, the costs due to MTBR* levels from 500 hours to 1500 hours and confidence levels of 30, 60,and 90 percent must be determined. The other two variables, probability of passing and demonstration duration, affect these costs. The following is a description of how values for these other two factors were chosen.

The Probability of Passing the Demonstration

In a contractual environment, the specific probability of passing would be selected through a cost trade-off procedure. The cost penalty of failing the demonstration would be evaluated against the cost to achieve an MTBR that would allow selection of an appropriate probability of passing. (This would probably be a joint contractor-customer decision, and the actual probability of passing agreed upon would be applicable only to that program.)

Figures 5 through 7 show the potential impact of this variable on test costs. These figures depict how the required MTBR (and therefore, costs)increases as the probability of passing increases. MTBR's* of 500, 1000, and 1500 hours are shown. The confidence level is 30 percent on Figure 5 and 90 percent on Figure 6. The fourth variable, demonstration duration, is held constant at 8000 hours for each of these figures. This variable is reduced to a fixed 2000 hours on Figure 7, which shows the 30 percent confidence level.

From these curves, the impact upon required MTBR of various probabilities of passing can be visualized. For the lower levels of MTBR*, the lower demonstrated confidence levels, or for longer demonstration length, 90 percent probability of passing does not appear to cost unreasonably more than 80 percent. However, for the 1500-hour MTBR* at 90 percent confidence, 90 percent probability of passing made necessary a required MTBR of 7240 hours, compared to only 5200 hours required MTBR for 80 percent probability of passing. Eighty percent was selected as a reasonable value for further analysis.

Demonstration Duration

The numerical impact of increases in demonstration duration upon the required MTBR in yielding specified levels of MTBR* and confidence at a fixed value of probability of passing is displayed in Figures 8 through 10. Each figure includes a 500- , 1000- , and 1500-hour MTBR* line and represents one confidence level. From the figures, it is apparent that the effect upon required MTBR (and therefore, costs) of varying demonstration duration is relatively insignificant at lower values of MTBR* or lower levels of confidence. However, the effect at the higher values is quite significant.

Because of this potentially large impact, the duration of the demonstration was <u>not</u> fixed. Instead, it was varied to produce the most cost-effective total program.

Of the four study variables affecting the required MTBR (output of Type II testing), the probability of passing was held constant, the demonstration test duration was optimized, and the MTBR* and confidence levels were the independent variables.

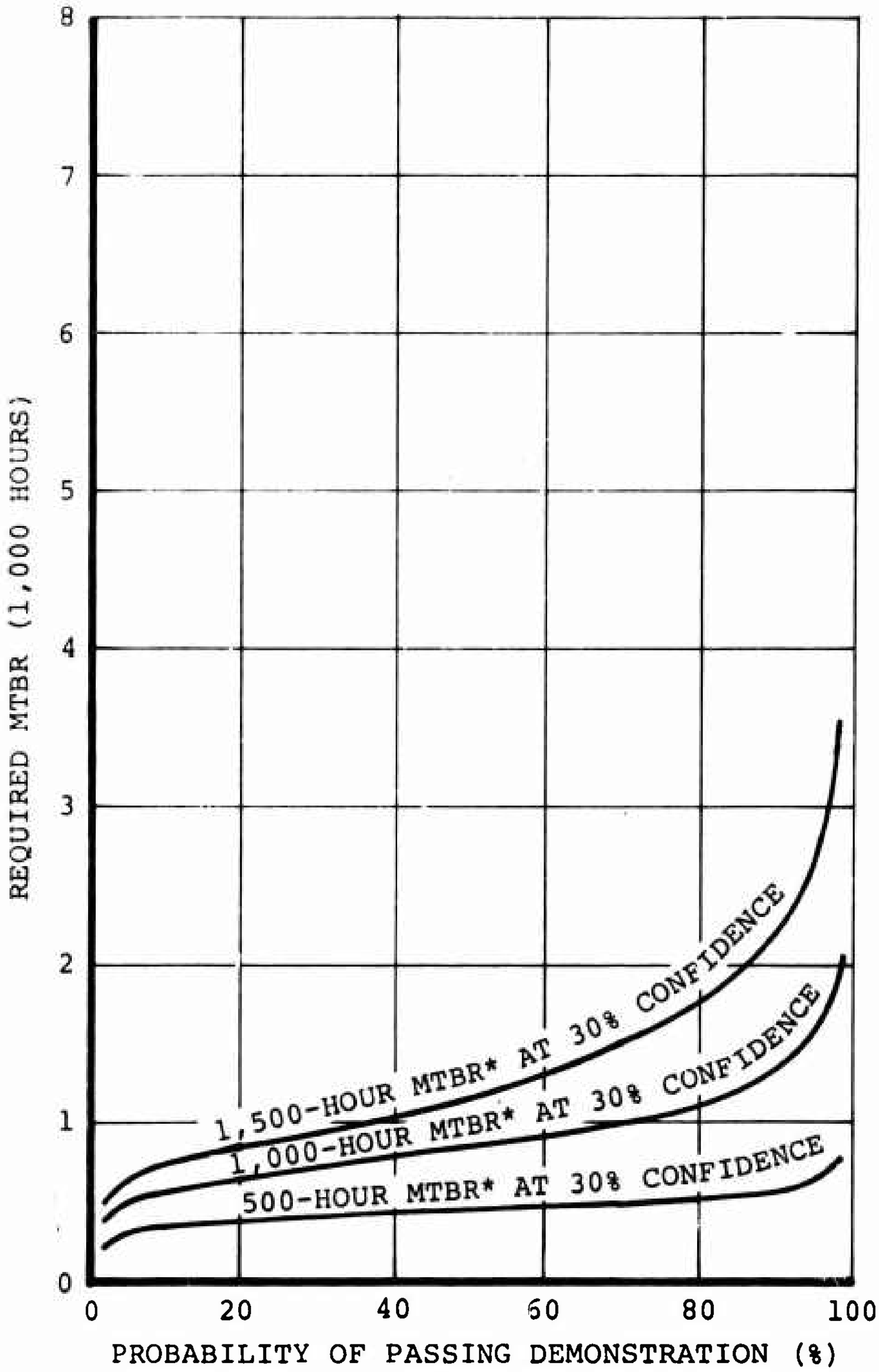


Figure 5. Comparison of Required MTBR to Probability of Passing 8,000-Hour Constant Duration Demonstration.

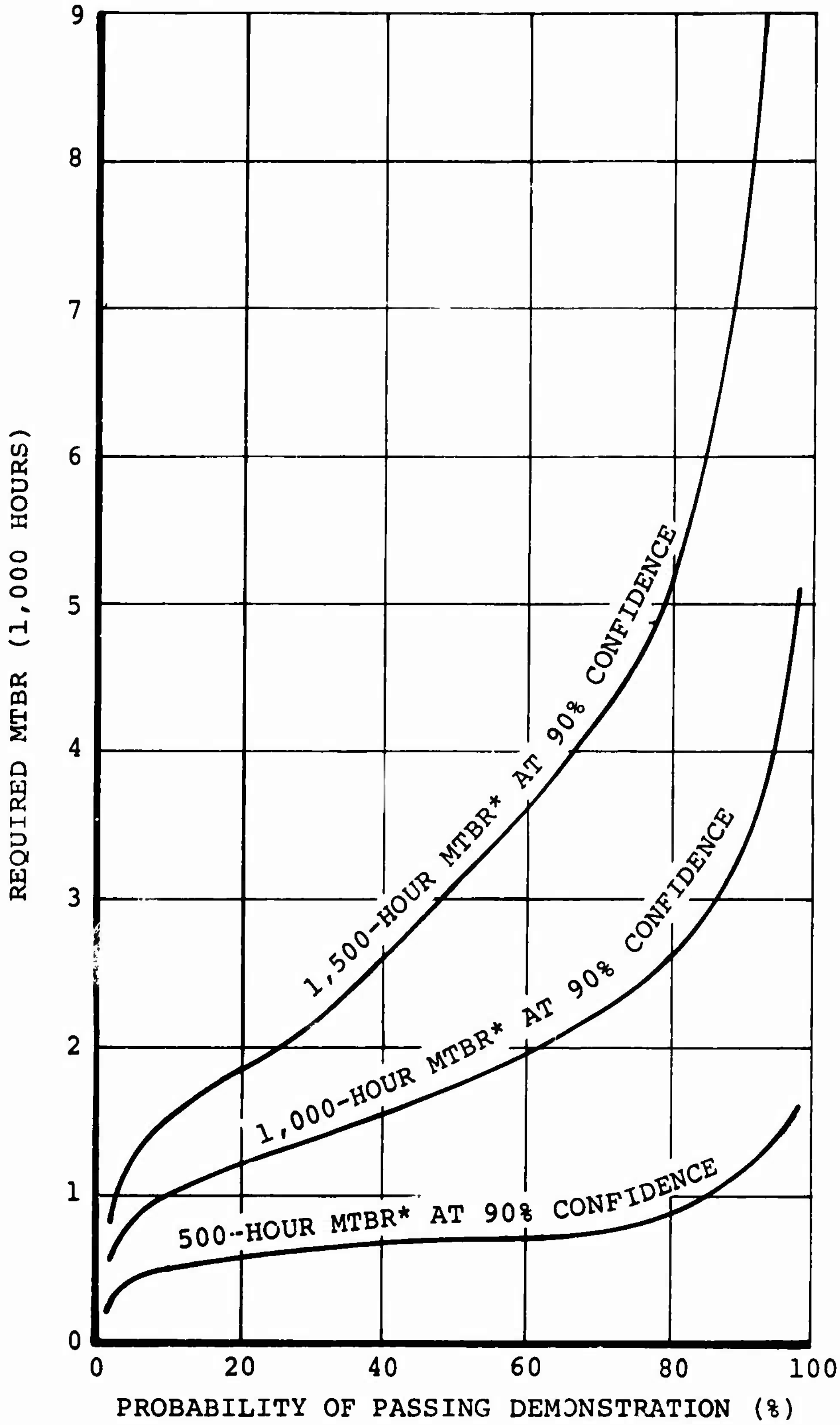


Figure 6. Comparison of Required MTBR to Probability of Passing 8,000-Hour Constant Duration Demonstration.

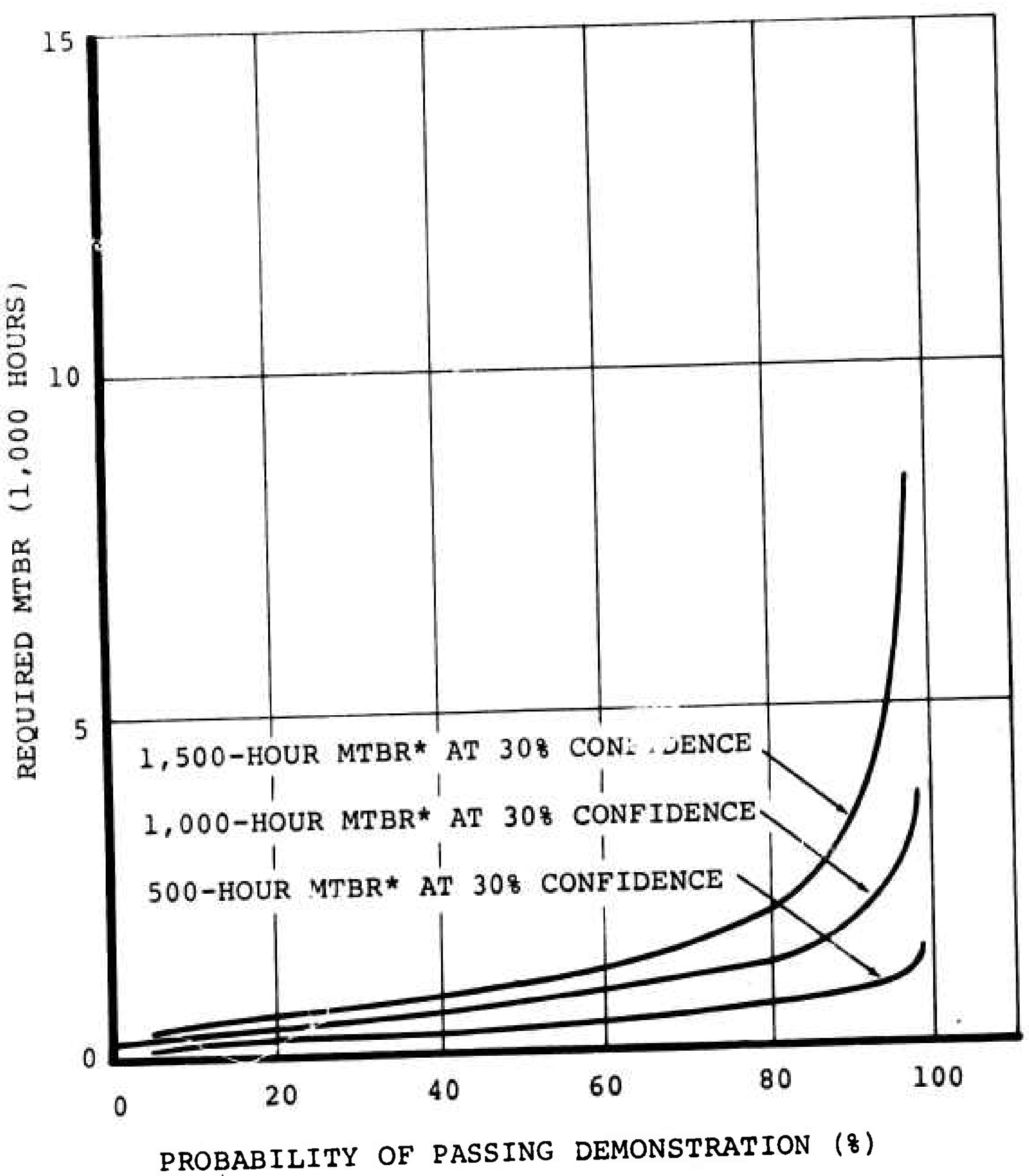


Figure 7. Comparison of Required MTBR to Probability of Passing 2,000-Hour Constant Duration Demonstration.

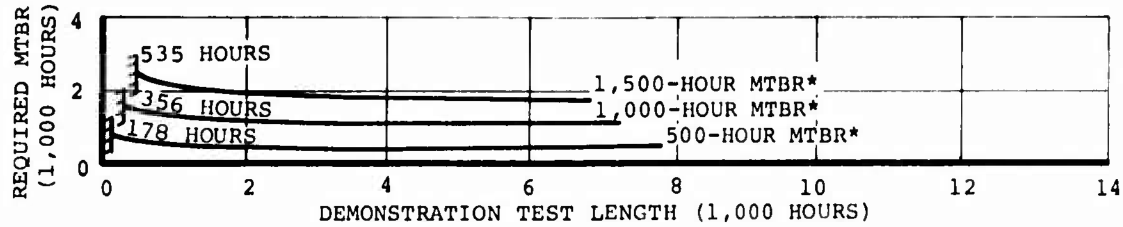


Figure 8. Comparison of Required MTBR to Demonstration Test Duration at 30% Confidence and 80% Probability of Passing Demonstration.

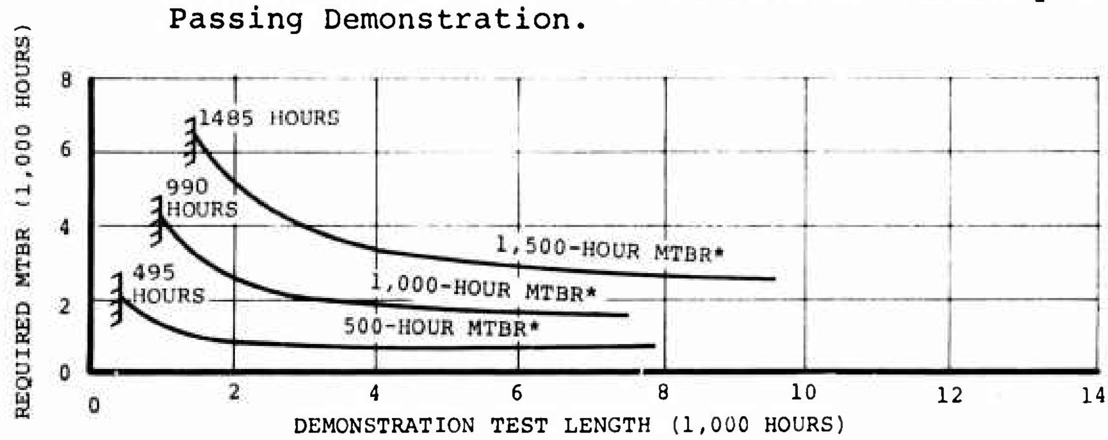


Figure 9. Comparison of Required MTBR to Demonstration Test Duration at 60% Confidence and 80% Probability of Passing Demonstration.

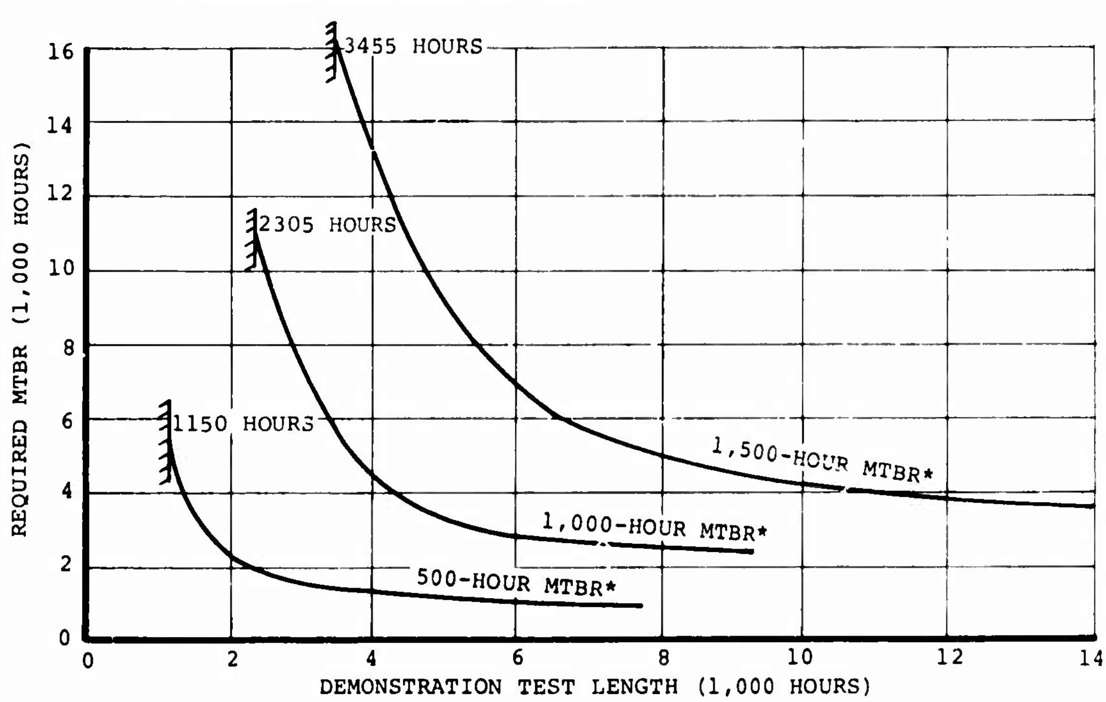


Figure 10. Comparison of Required MTBR to Demonstration Test Duration at 90% Confidence and 80% Probability of Passing Demonstration.

With the input (MTBR off the board) and the procedure for determining the required MTBR defined, the amount of Type II testing required and the optimum mix of techniques can be determined.

ANALYSIS OF PROBLEM IDENTIFICATION TESTING

Applicable Test Techniques

Measurement of the cost and effectiveness of alternate test techniques is possible once the following parameters are defined for each test technique:

1. Test effectiveness - the ability to detect and correct problems
2. Test costs - both nonrecurring and recurring
3. Test schedules - both lead time for fixtures or specimens, and operating rate of test

In this section, these characteristics are quantified for the potential test techniques that are considered practical for future use in a Helicopter "A" test program.

This study concentrates on determining the cost effectiveness of the core techniques for the major dynamic components. These techniques must detect the majority of problems. The non-core tests find problems caused by extreme climatic conditions (e.g., the climatic environmental tests conducted at Yuma, Eglin, or Alaska). The core test techniques used on the CH-47 for Type II testing are presented in Appendix III.

The major dynamic systems tests were:

1. Closed loop transmission test stand (Figure 11)
2. Main rotor whirl tower (Figure 12)
3. Rotor head hinge bearing stand
4. Rotor controls assembly test rig (Figure 13)
5. Aft vertical shaft bearing full shaft rig (Figure 14)
6. Aft vertical shaft bearing back-to-back rig
7. Tiedown aircraft (Figure 15)

Additional tests that were performed to investigate specific problems on the CH-47 employed new test techniques. Although these Type III tests were not supported out of developmental

funds, they provided a pool of new test techniques which can be considered for possible incorporation in future programs. These test techniques are detailed in Appendix III as Type III tests (on the CH-47). Some of these tests are:

1. Transmission gear resonance test (Figure 16)

2. Transmission clutch test (no load)

3. Transmission oil scavenge flow test

4. Blade tip cover fatigue test (Figure 17)

5. Rotor head droop stop pounding

6. Rotor blade water entrapment

7. Rotor controls back-to-back test (Figure 18)

Except for the rotor controls back-to-back test, these test techniques were created to reproduce a specific failure mode and verify a new design. For the rotor controls test, the new technique performed the same function as the old, but at less cost per test hour and with a faster accumulation of total specimen test hours.

In some cases, tests were performed on elements of an assembly (i.e., gear resonance test), on a subassembly (i.e., blade tip cover), or on an entire assembly (i.e., blade water entrapment).

With the exception of the rotor controls test, these newer test techniques have been created to detect (reproduce) only one failure mode. If it was determined that a new model aircraft had these potential problems inherent in the design, tests such as these would be performed in addition to the basic Type I and II tests. These tests would be Type I in nature, since they would not be varied in duration as a function of the MTBR objective. Of these newer test techniques, only the rotor controls assembly back-to-back test is an additional candidate for Type II testing.

Additional candidate techniques are used elsewhere in the industry, but were not performed on the CH-47. The most attractive of these techniques are:

1. Open loop drive system test (Figure 19)

2. Dynamic systems test (Reference 2)

Not all of the above candidate Type II test techniques are applicable to a test program for Helicopter "A". Test tech-

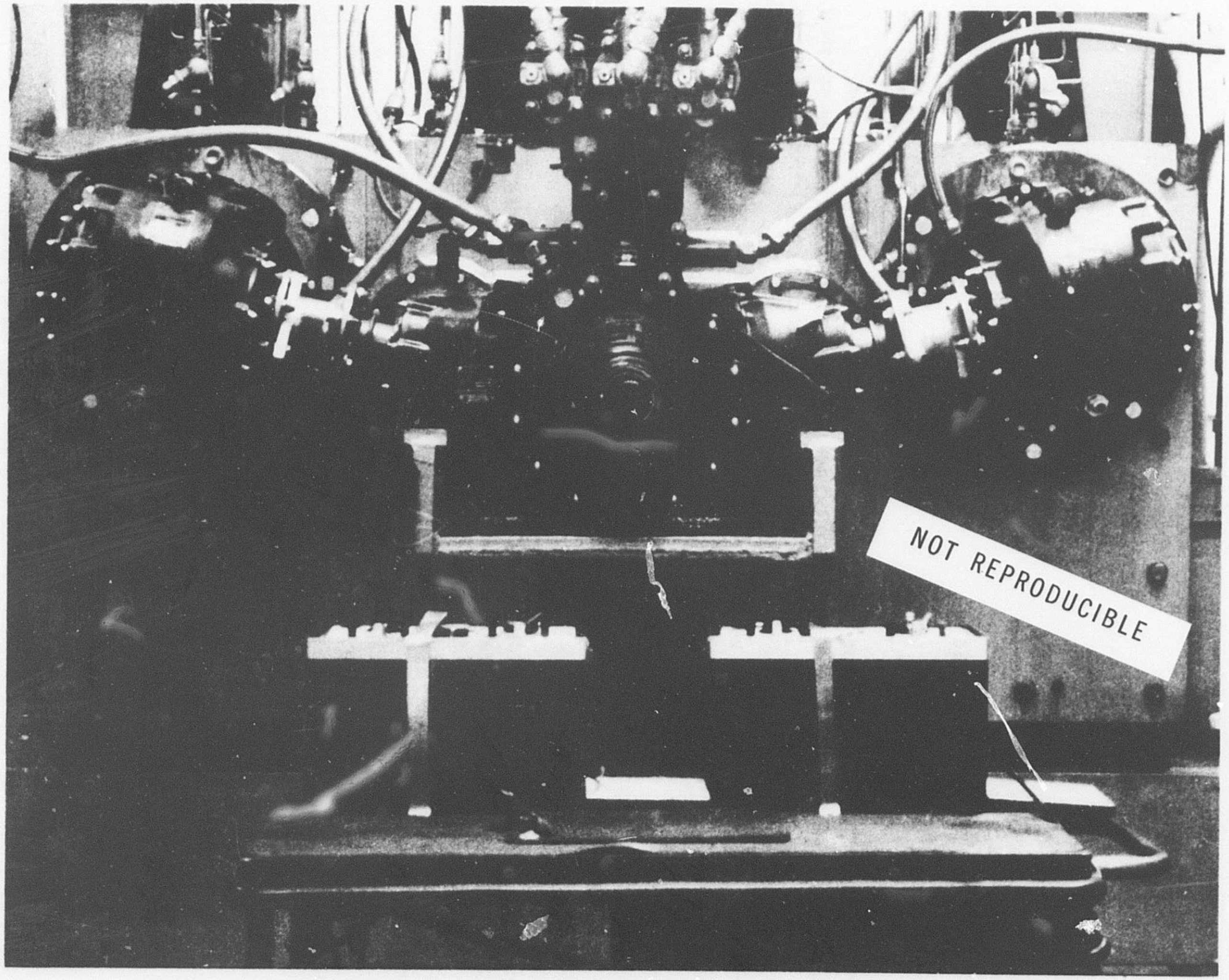


Figure 11. Closed Loop Transmission Test Stand.

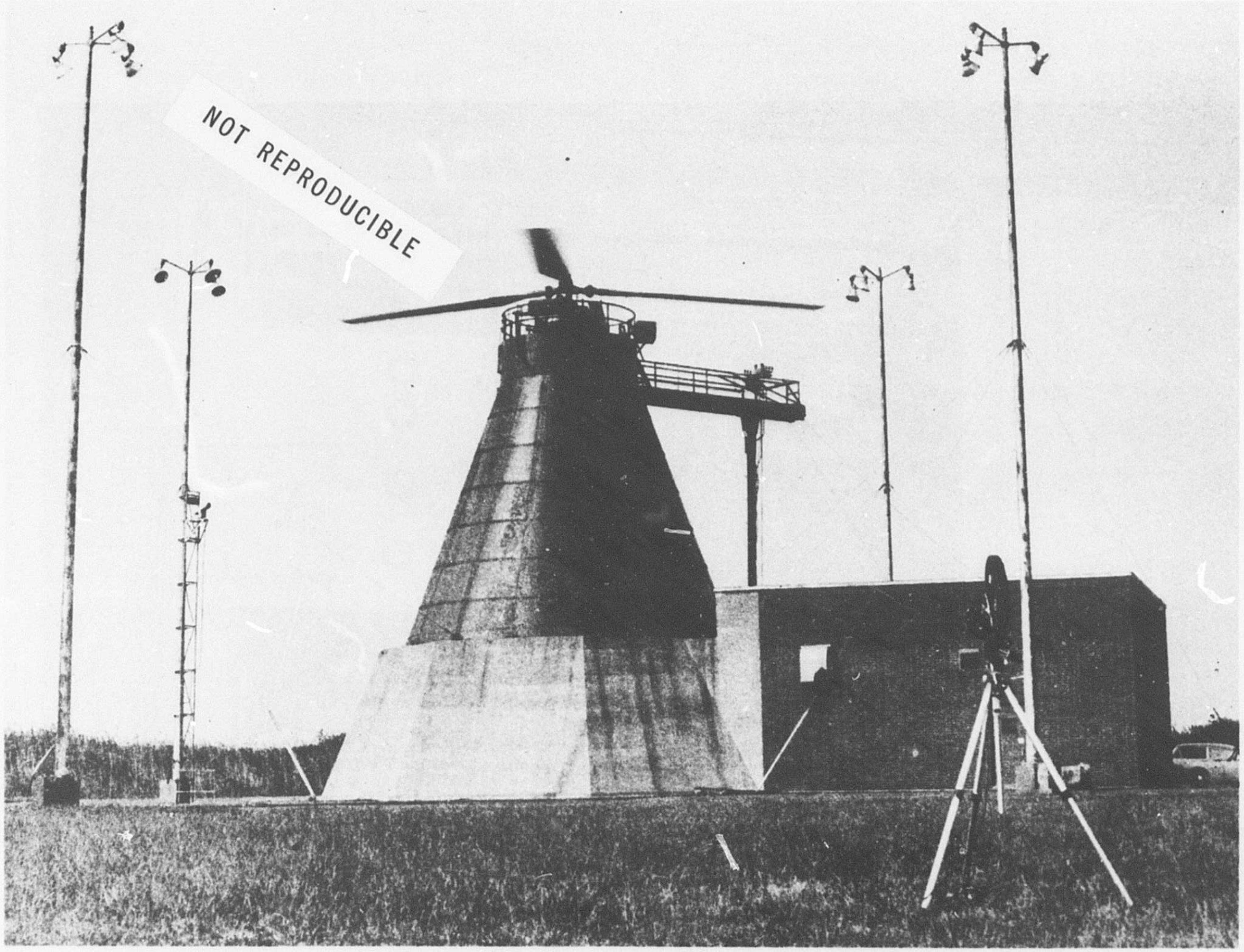


Figure 12. Main Rotor Whirl Tower.

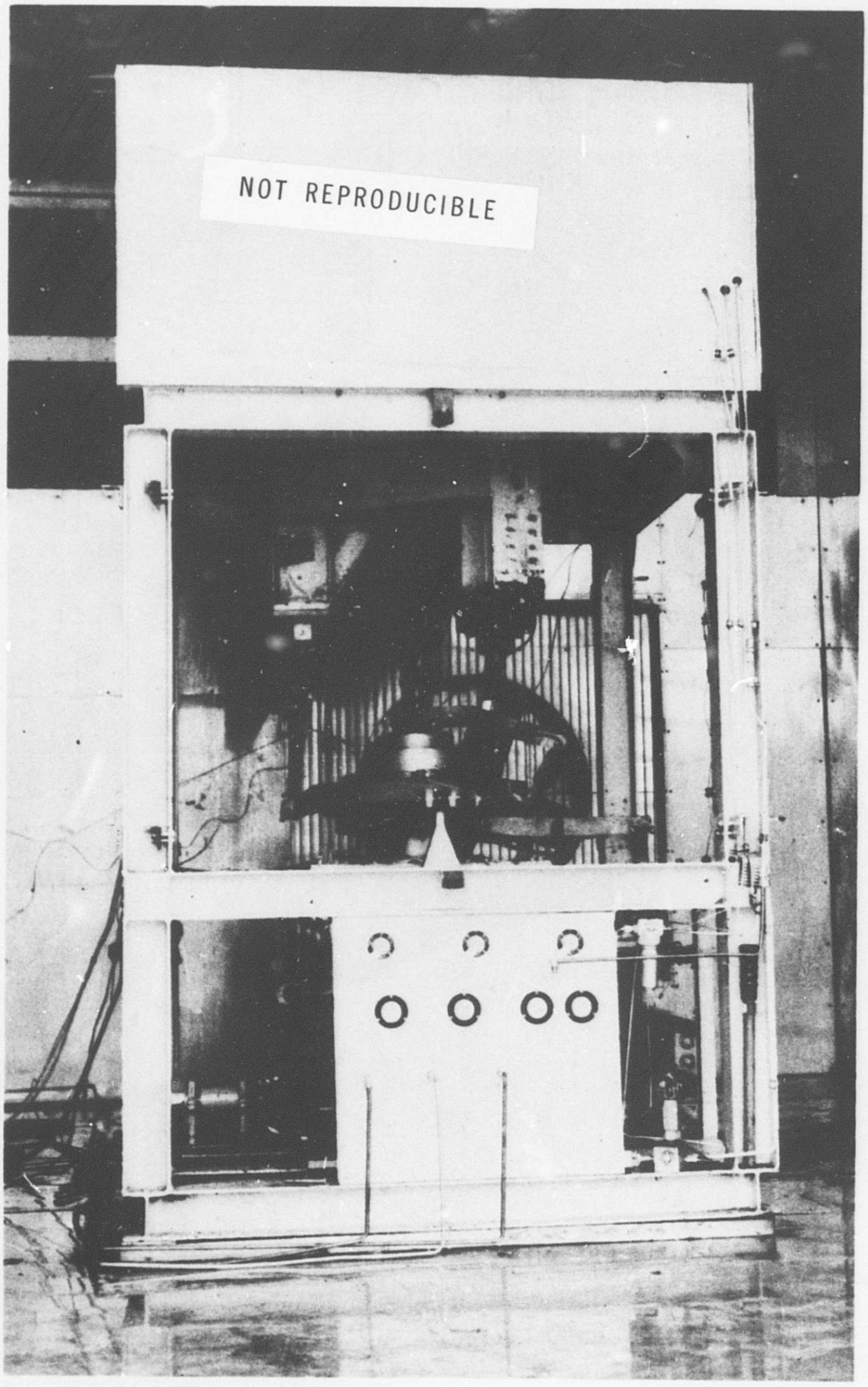


Figure 13. Single Specimen in Rotor Controls Assembly Test Rig.

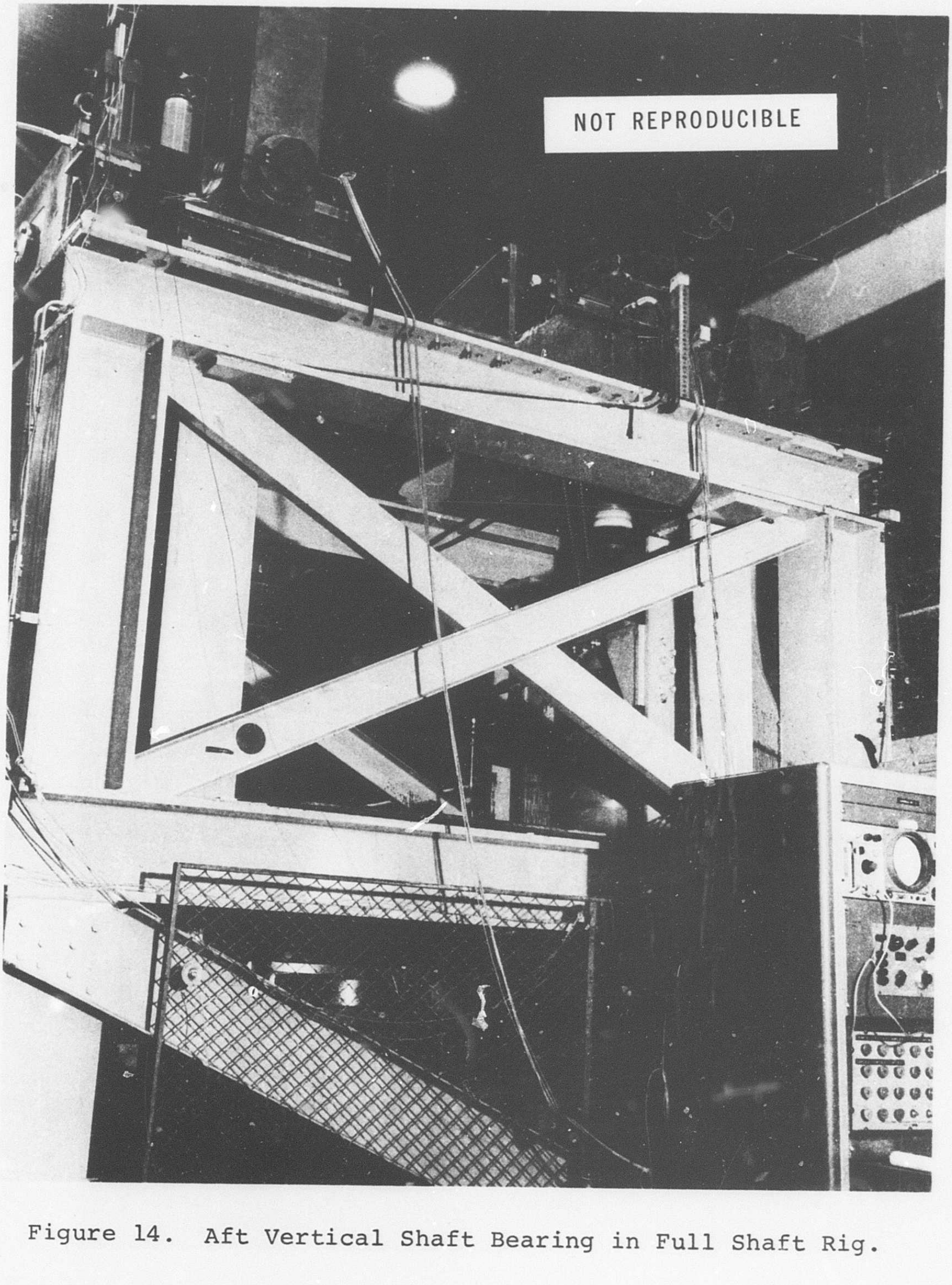


Figure 14. Aft Vertical Shaft Bearing in Full Shaft Rig.

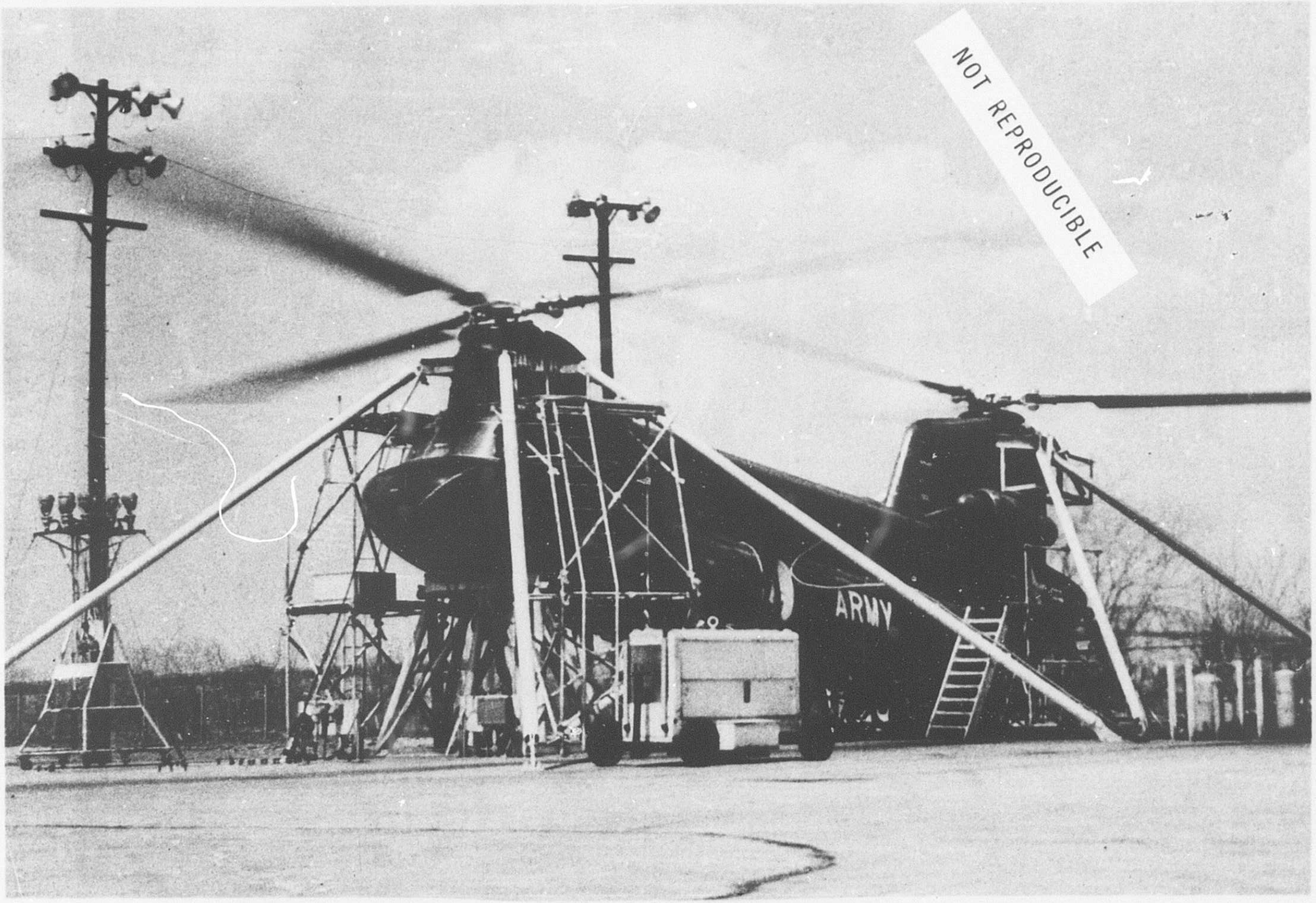


Figure 15. Tiedown Aircraft.

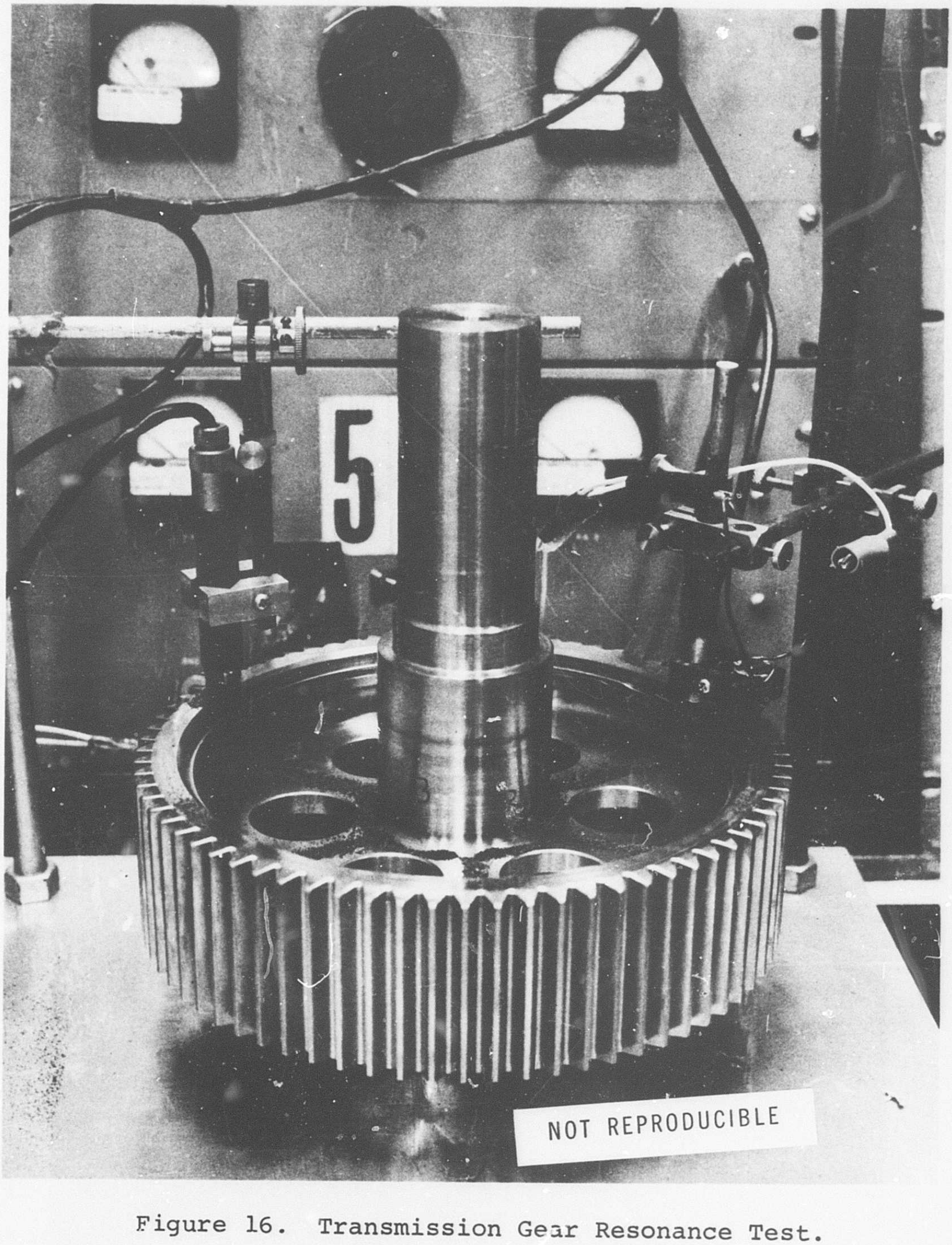


Figure 16. Transmission Gear Resonance Test.

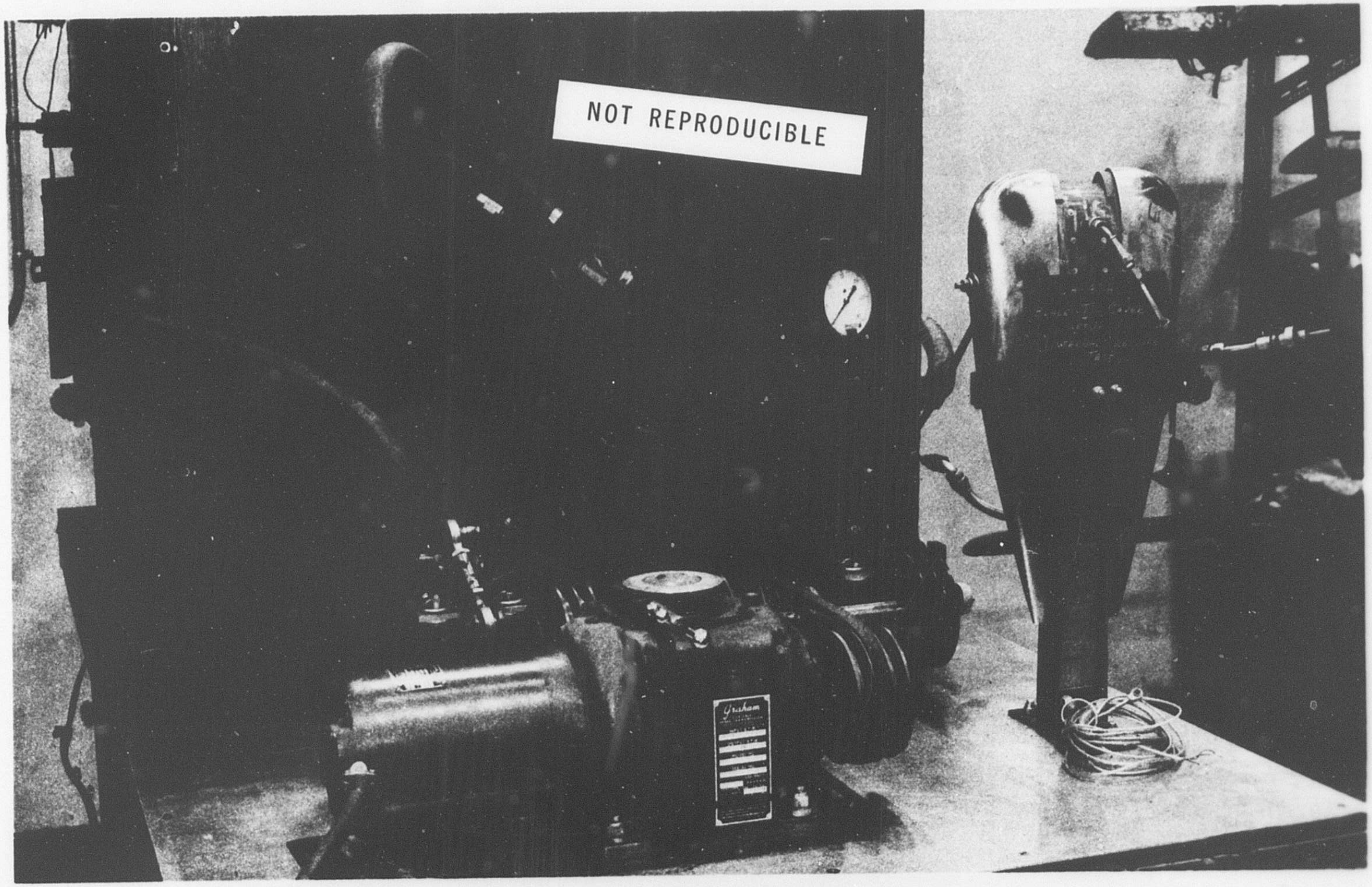


Figure 17. Blade Tip Cover Fatigue Test.

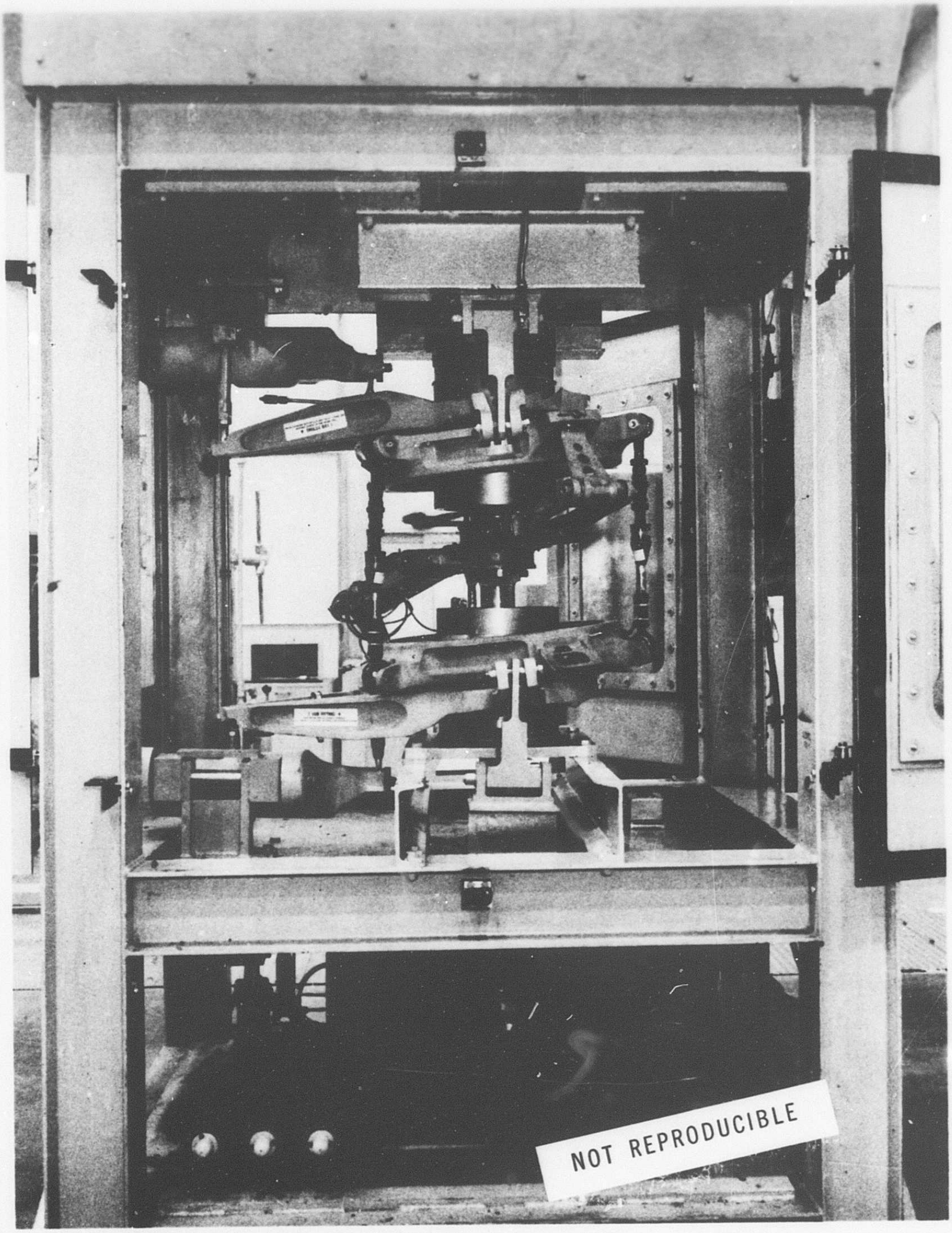


Figure 18. Rotor Controls Back-to-Back Test Rig.

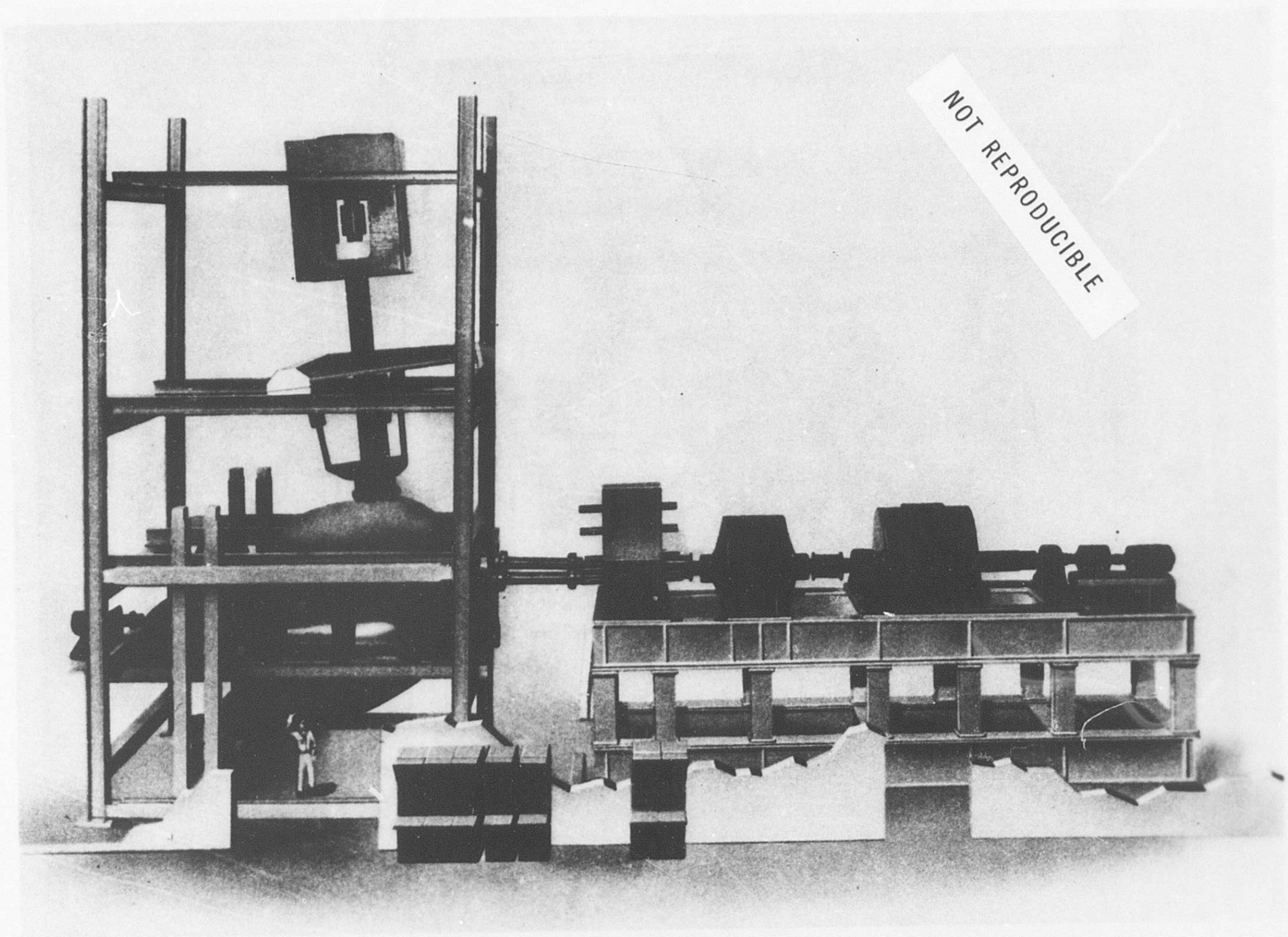


Figure 19. Open Loop Drive System Test Rig.

niques involving a separate aft thrust bearing and swashplate rotor head bearings are not applicable to Helicopter "A" because of configuration differences. Conversely, the tail rotor system on Helicopter "A" requires test techniques not used on the CH-47. The candidate test techniques for Helicopter "A" which were considered appropriate are tabulated on Table I.

The study now proceeds to quantification of each technique's cost effectiveness. Once quantified, the cost effectiveness of each technique will be used to evaluate combinations of techniques arranged into test programs.

Test Technique Effectiveness

Effectiveness is defined as the ability of a test technique to detect a potential field problem. Correction of problems after they are detected does not differ significantly among test techniques. Therefore, the main concern is the detection ability of each test technique.

In support of this evaluation, CH-47 test and service experience was reviewed. All significant CH-47 problems were listed by component (Appendix II). (Identification symbols indicate the ability of each test technique to detect each CH-47 failure mode.)

Table II summarizes the CH-47 problem detection experience and indicates that a large percentage (74 percent) of problems were detected by the total test program. However, no individual test technique detected all the problems that were detected by the total test program. Analysis of individual failure modes and their detection histories suggested that the full detection potential of each test technique was not manifested in the historical test results. Specifically, many problems were not detected during certain tests because of reasons which are completely unrelated to the actual test techniques employed. For purposes of this analysis, these reasons are termed artificial restraints. The term inherent restraints is used for those test technique limitations which stem from the specific loads, speeds, configurations, or climatic environments (dust, humidity, temperature, etc.) of each test technique.

The artificial restraints observed in the CH-47 test program can be classified in the following groups:

1. Configuration

   Many problems which first appeared in early tests were completely corrected. Later test specimens incorporated these design changes and therefore did not fail during subsequent test techniques.

TABLE I. HELICOPTER "A" CANDIDATE TEST TECHNIQUES (CORE ONLY)

Test Technique	Helicopter "A" Components								
	Main Trans-mission Gearbox	Main Trans-mission Controls	Main Trans-mission Hub	Main Rotor Blades	Tail Drive Shaft	Inter-mediate Gearbox	Tail Rotor Trans-mission	Tail Rotor Hub	Tail Rotor Blade
Closed Loop Stand	X	-	-	-	-	-	-	-	-
Rotor Controls Rig	-	X	-	-	-	-	-	-	-
Rotor Controls Back-to-Back Rig	-	X	-	-	-	-	-	-	-
Whirl Tower	-	X	X	X	-	-	-	-	-
Open Loop Stand	X	X	-	-	-	-	-	-	-
Tail Rotor Whirl Stand	-	-	-	-	X	X	X	X	X
Dynamic Systems Test	X	X	X	X	X	X	X	X	X
Tiedown Aircraft	X	X	X	X	X	X	X	X	X
Flight Test	X	X	X	X	X	X	X	X	X

TABLE II. SUMMARY OF PROBLEMS ACTUALLY DETECTED IN CH-47 TEST PROGRAM

Component	(1) Test Only		(2) Field and Test		(3) Summary of (1) and (2)		(4) Field Only		(5) Total
	No.	%	No.	%	No.	%	No.	%	No.
Forward Transmission	15	33	18	40	33	73	12	27	45
Aft Transmission	16	32	24	48	40	80	10	20	50
Combining Transmission	4	15	18	70	22	85	4	15	26
Engine Transmissions	4	14	18	64	22	78	6	22	28
Subtotal (Transmissions)	39	26	78	52	117	78	32	22	149
Shafting	5	20	11	44	16	64	9	36	25
Rotor Controls	5	22	13	56	18	78	5	22	23
Rotor Head	2	6	16	52	18	58	13	42	31
Rotor Blades	4	15	15	58	19	73	7	27	26
Total	55	22	133	52	188	74	66	26	254

NOTE: Absolute values in each block indicate number of problems detected. Percentage values are percentage of total problems in Column 5.

In other cases, a failure mode caused by a manufacturing or material error may happen to appear in a specimen that is being tested by a given test technique. Other test techniques could have detected the failure mode if the necessary conditions were present in the specimen.

2. Maintenance

An entire class of failure modes is induced by maintenance damage. Often, detection of these modes during test does not occur because of the unreal maintenance environment. The manner in which the hardware is installed in the test fixture may also preclude the appearance of the maintenance-induced problem.

3. Test Acceptance Criteria

A significant number of problems actually occurred during tests but were not recorded, reported, or corrected because the criteria under which the test was operating did not require such recognition. Failure modes which involve a measure of degree (e.g., wear, fretting, leakage) are particularly susceptible to being overlooked. Emphasis is placed upon those modes which cause the component to fail to operate.

4. Test Procedures

In certain cases, the design contained features which were not used during testing. In-service use of these features resulted in subsequent failures. For example, a quick-disconnect feature was incorporated into the lag damper/rotor head assembly. Utilization of this feature in the field soon resulted in the discovery of an understrength sheet metal bracket, the repair of which required rotor head removal. Exercising this quick-disconnect feature during whirl tower testing would have brought out the full problem detection potential of the whirl tower test.

All of the above artificial restraints prevented many problems from being detected by specific test techniques. They should not, however, detract from the problem-detection potential of a given test technique. Also, a test technique might not have been operated for sufficient duration to detect the problem. If a failure mode has a mean time to failure (MTBF) in excess of the test duration, it will have a low probability of appearance despite the fact that there were no inherent restraints.

For these reasons, the comparison of test and field-identified problems (Appendix II) is in the form of four classifications identified with separate symbols. These symbols and their meanings are as follows:

● Problem was actually detected during test technique

⊕ Problem could have been detected except for the presence of artificial restraints

O Problem could have been detected if test had been operated for sufficient duration

X Problem cannot be detected because of inherent restraints

The full detection potential of any test technique is therefore represented by the sum of the first three groups. The detailed analysis of the CH-47 failure modes and the detection potential of test techniques utilized and other new test techniques is presented as Appendix II. This appendix is summarized for each component on Tables III through XII. Table III is the summary for the entire dynamic system. These tables indicate the number of CH-47 problems that cannot be detected on each of the test techniques due to artificial or inherent restraints. An overview of inherent restraints classifications on Table III is provided in Figure 20. Here the three types of inherent restraints are displayed for the three levels of core techniques (bench, tiedown/DST, and flight) and the climatic tests (Alaska and Yuma). This figure concludes that the test techniques applied to the CH-47 had the potential for detecting all but two failure modes or 1 percent of the total 254 failure modes. In other words, of the 26 percent of the problems not detected on the CH-47 (Table II), most were due to inadequate duration.

Table XIII further refines this data and presents a component-by-component quantification of the effectiveness of each candidate test technique. Effectiveness is expressed as a percentage of the total failure modes that each test technique can detect considering the inherent restraints unique to that test technique.

From the CH-47 data and with the specific configuration of Helicopter "A", a series of effectiveness percentages was developed for those test techniques applicable to Helicopter "A". These percentages (shown on Table XIV) represent the ultimate ability of each test technique (when operated for infinite duration) to detect the potential failure modes in each of the Helicopter "A" components. However, a percentage of total problems is not an adequate parameter with which to size problem identification test duration. These percentages

TABLE III. COMPARISON SUMMARY OF FIELD AND TEST PROBLEMS FOR ALL CH-47 COMPONENTS

(Symbol)	Detection Potential	CH-47 Test Techniques						New Test Techniques	
		Bench and Whirl	Tie-down	Flight Test	Eglin	Yuma	Alaska	Dynamic Systems	Bench and Whirl
(●)	Did Detect	78	97	35	11	10	13		
(⊕)	Could Detect with Artificial Restraints Removed								
	1) Configuration	26	41	51	51	55	53		
	2) Maintenance	11	14	12	17	16	17		
	3) Test Acceptance Criteria	18	14	8	9	8	10		
	4) Test Procedures	5	4	2	2	2	2		
(O)	Could Detect with Adequate Time								
	1) 100 Hours	-	-	-	2	3	3	27	27
	2) 500 Hours	9	4	23	24	27	27	48	48
	3) 1,000 Hours	4	4	36	31	36	34	36	37
	4) 3,000 Hours	16	17	23	29	28	25	37	37
	5) 5,000 Hours	5	8	13	12	14	14	15	15
	6) 10,000 Hours	6	6	9	9	10	10	22	20
	7) 30,000 Hours	3	2	3	3	5	4	4	4
	8) 50,000 Hours	5	5	8	7	8	8	12	12
	9) 100,000 Hours	15	15	27	27	28	28	29	29
	Subtotal	201	231	250	234	250	248	230	229
(X)	Inherent Restraints (Cannot Detect)								
	1) Environmental	11	4	4	5	4	6	9	10
	2) Loads	20	19	-	15	-	-	15	13
	3) Configuration	22	-	-	-	-	-	-	2
	Total	254	254	254	254	254	254	254	254

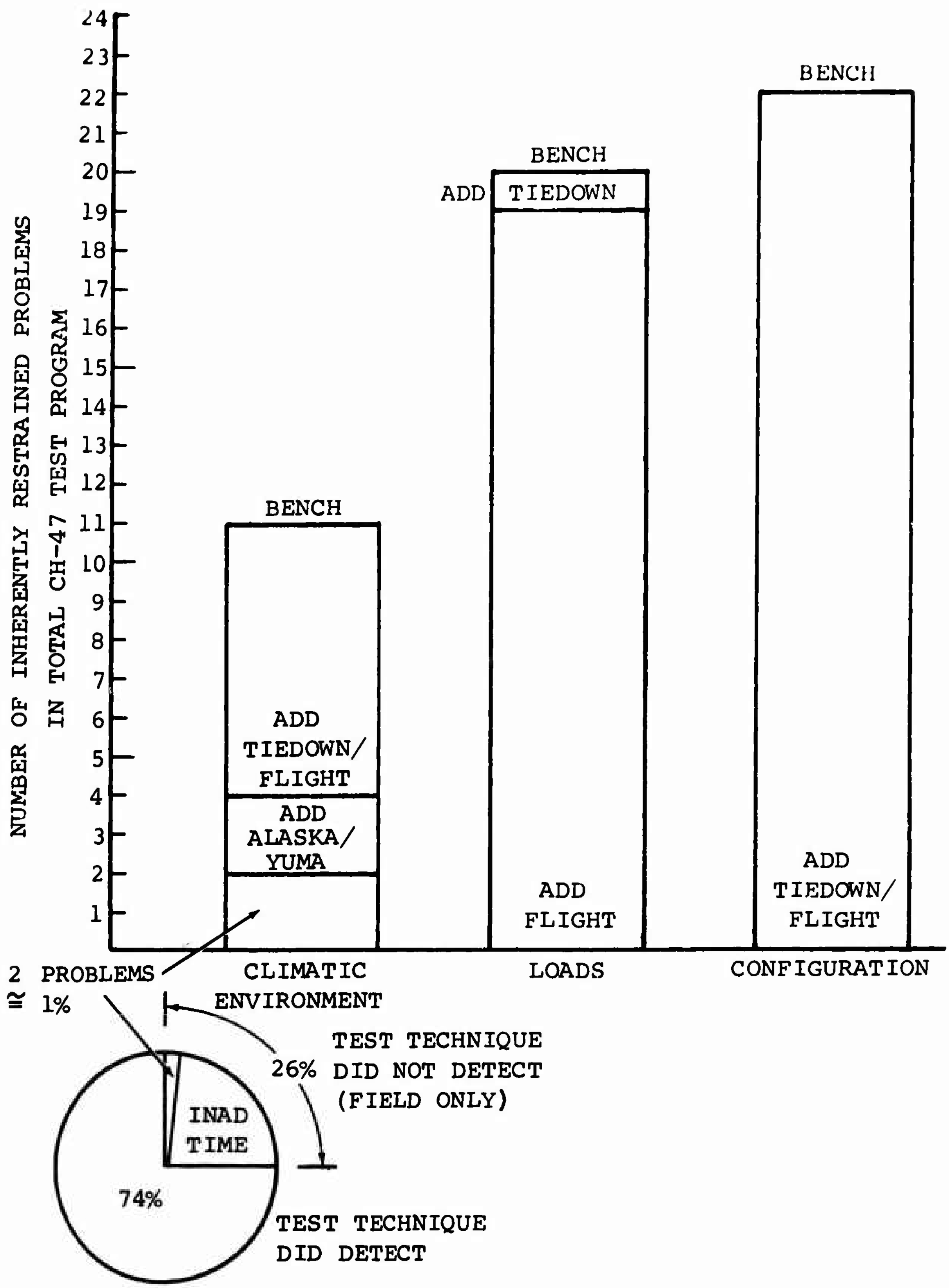


Figure 20. Categories of CH-47 Inherent Restraints.

TABLE IV. COMPARISON SUMMARY OF FIELD AND TEST PROBLEMS FOR ALL CH-47 TRANSMISSIONS

(Symbol)	Detection Potential	CH-47 Test Techniques: Closed Loop Bench Endurance	Tie-down	Flight Test	Eglin	Yuma	Alaska	New Test Techniques: Open Loop Bench Endurance	Dynamic Systems
(●)	Did Detect	58	66	15	4	4	3		
(◍)	Could Detect with Artificial Restraints Removed								
	1) Configuration	14	28	35	38	38	39		
	2) Maintenance	6	7	7	9	8	9		
	3) Test Acceptance Criteria	13	7	3	3	3	4		
	4) Test Procedures	2	2	-	-	-	-		
(O)	Could Detect with Adequate Time								
	1) 100 Hours	-	-	-	-	-	-	14	14
	2) 500 Hours	8	-	15	16	16	16	35	35
	3) 1,000 Hours	4	1	18	19	19	19	23	23
	4) 3,000 Hours	10	10	12	17	17	15	19	19
	5) 5,000 Hours	4	4	8	6	7	8	7	7
	6) 10,000 Hours	5	4	7	7	7	7	16	17
	7) 30,000 Hours	1	1	1	2	2	2	2	2
	8) 50,000 Hours	5	5	7	7	7	7	9	9
	9) 100,000 Hours	9	9	20	19	20	20	20	20
	Subtotal	139	144	148	147	148	149	145	146
(X)	Inherent Restraints (Cannot Detect)								
	1) Environmental	2	1	1	-	1	-	2	1
	2) Loads	8	4	-	2	-	-	2	2
	Total	149	149	149	149	149	149	149	149

TABLE V. COMPARISON SUMMARY OF FIELD AND TEST PROBLEMS FOR CH-47 FORWARD TRANSMISSIONS

(Symbol)	Detection Potential	CH-47 Test Techniques						New Test Techniques	
		Closed Loop Bench Endurance	Tie-down	Flight Test	Eglin	Yuma	Alaska	Open Loop Bench Endurance	Dynamic Systems
(●)	Did Detect	17	15	6	-	-	-		
(◉)	Could Detect with Artificial Restraints Removed								
	1) Configuration	3	10	13	15	15	15		
	2) Maintenance	2	2	2	3	3	3		
	3) Test Acceptance Criteria	2	1	-	-	-	-		
	4) Test Procedures	-	-	-	-	-	-		
(O)	Could Detect with Adequate Time								
	1) 100 Hours	-	-	-	-	-	-	5	5
	2) 500 Hours	3	-	3	3	3	3	12	12
	3) 1,000 Hours	-	-	7	7	7	7	8	8
	4) 3,000 Hours	4	4	1	4	4	4	4	4
	5) 5,000 Hours	2	1	3	2	3	3	2	2
	6) 10,000 Hours	3	3	4	4	4	4	6	7
	7) 30,000 Hours	1	1	1	1	1	1	1	1
	8) 50,000 Hours	1	2	2	2	2	2	2	2
	9) 100,000 Hours	1	2	3	2	3	3	2	2
	Subtotal	39	41	45	43	45	45	42	43
(X)	Inherent Restraints (Cannot Detect)								
	1) Environmental	1	-	-	-	-	-	1	-
	2) Loads	5	4	-	2	-	-	2	2
	Total	45	45	45	45	45	45	45	45

TABLE VI. COMPARISON SUMMARY OF FIELD AND TEST PROBLEMS FOR CH-47 AFT TRANSMISSIONS

(Symbol)	Detection Potential	CH-47 Test Techniques						New Test Techniques	
		Closed Loop Bench Endurance	Tie-down	Flight Test	Eglin	Yuma	Alaska	Open Loop Bench Endurance	Dynamic Systems
(●)	<u>Did Detect</u>	24	24	2	2	1	-		
(●)	<u>Could Detect with Artificial Restraints Removed</u>								
	1) Configuration	2	13	16	16	16	17		
	2) Maintenance	-	1	1	1	1	1		
	3) Test Acceptance Criteria	3	1	-	-	-	-		
	4) Test Procedures	1	1	-	-	-	-		
(O)	<u>Could Detect with Adequate Time</u>								
	1) 100 Hours	-	-	-	-	-	-	4	4
	2) 500 Hours	3	-	5	6	6	6	11	11
	3) 1,000 Hours	-	-	4	5	5	5	8	8
	4) 3,000 Hours	4	3	5	5	5	5	5	5
	5) 5,000 Hours	2	2	3	2	3	3	3	3
	6) 10,000 Hours	2	1	3	3	3	3	6	6
	7) 30,000 Hours	-	-	-	-	-	-	-	-
	8) 50,000 Hours	2	2	3	3	3	3	5	5
	9) 100,000 Hours	5	1	7	7	7	7	7	7
	Subtotal	48	49	49	50	49	50	49	49
(X)	<u>Inherent Restraints (Cannot Detect)</u>								
	1) Environmental	1	1	1	-	1	-	1	1
	2) Loads	1	-	-	-	-	-	-	-
	Total	50	50	50	50	50	50	50	50

TABLE VII. COMPARISON SUMMARY OF FIELD AND TEST PROBLEMS FOR CH-47 COMBINING TRANSMISSIONS

(Symbol)	Detection Potential	CH-47 Test Techniques						New Test Techniques	
		Closed Loop Bench Endurance	Tie-down	Flight Test	Eglin	Yuma	Alaska	Open Loop Bench Endurance	Dynamic Systems
(●)	Did Detect	6	14	4	1	1	-		
(●)	Could Detect with Artificial Restraints Removed								
	1) Configuration	5	1	4	5	5	5		
	2) Maintenance	3	3	3	4	4	4		
	3) Test Acceptance Criteria	5	2	2	1	1	2		
	4) Test Procedures	-	-	-	-	-	-		
(O)	Could Detect with Adequate Time								
	1) 100 Hours	-	-	-	-	-	-	3	3
	2) 500 Hours	-	-	-	-	-	-	2	2
	3) 1,000 Hours	3	-	4	4	4	4	4	4
	4) 3,000 Hours	2	3	4	6	6	6	8	8
	5) 5,000 Hours	-	-	-	-	-	-	-	-
	6) 10,000 Hours	-	-	-	-	-	-	3	3
	7) 30,000 Hours	-	-	-	-	-	-	-	-
	8) 50,000 Hours	1	-	1	1	1	1	1	1
	9) 100,000 Hours	1	3	4	4	4	4	5	5
	Subtotal	26	26	26	26	26	26	26	26
(X)	Inherent Restraints (Cannot Detect)								
	1) Environmental	-	-	-	-	-	-	-	-
	2) Loads	-	-	-	-	-	-	-	-
	Total	26	26	26	26	26	26	26	26

TABLE VIII. COMPARISON SUMMARY OF FIELD AND TEST PROBLEMS FOR CH-47 ENGINE TRANSMISSIONS

(Symbol)	Detection Potential	CH-47 Test Techniques: Closed Loop Bench Endurance	Tie-down	Flight Test	Eglin	Yuma	Alaska	New Test Techniques: Open Loop Bench Endurance	Dynamic Systems
(●)	Did Detect	11	13	3	1	2	3		
(●)	Could Detect with Artificial Restraints Removed								
	1) Configuration	4	4	2	2	2	2		
	2) Maintenance	1	1	1	1	-	1		
	3) Test Acceptance Criteria	3	3	1	2	2	2		
	4) Test Procedures	1	1	-	-	-	-		
(O)	Could Detect with Adequate Time								
	1) 100 Hours	-	-	-	-	-	-	2	2
	2) 500 Hours	2	-	7	7	7	7	10	10
	3) 1,000 Hours	1	1	3	3	3	3	3	3
	4) 3,000 Hours	-	-	2	2	2	-	2	2
	5) 5,000 Hours	-	1	2	2	2	2	2	2
	6) 10,000 Hours	-	-	-	-	-	-	1	1
	7) 30,000 Hours	-	-	-	1	1	1	1	1
	8) 50,000 Hours	1	1	1	1	1	1	1	1
	9) 100,000 Hours	2	3	6	6	6	6	6	6
	Subtotal	26	28	28	28	28	28	28	28
(X)	Inherent Restraints (Cannot Detect)								
	1) Environment	-	-	-	-	-	-	-	-
	2) Loads	2	-	-	-	-	-	-	-
	Total	28	28	28	28	28	28	28	28

TABLE IX. COMPARISON SUMMARY OF FIELD AND TEST PROBLEMS FOR CH-47 DRIVE SHAFTING

(Symbol)	Detection Potential	CH-47 Test Techniques: Aft Thrust Bearing Back-to-Back	Aft Thrust Bearing Full Stand	Bench Closed Loop	Tie-down	Flight Test	Eglin	Yuma	Alaska	New Test Techniques: Shafting Rigs Not Aft	Add Shafting To Closed Loop	Open Loop Trans-mission Stand Shafting	Dynamic Systems
(●)	Did Detect	2	1	1	9	8	-	-	1				
(●)	Could Detect with Artificial Restraints Removed												
	1) Configuration	-	-	-	-	2	2	2	2				
	2) Maintenance	1	2	2	3	2	3	3	3				
	3) Test Acceptance Criteria	1	1	1	2	2	1	1	1				
	4) Test Procedures	-	-	-	-	-	-	-	-				
(O)	Could Detect with Adequate Time												
	1) 100 Hours	-	-	-	-	-	-	1	1	1	1	1	1
	2) 500 Hours	-	-	-	1	1	2	4	3	3	2	2	2
	3) 1,000 Hours	-	-	-	1	4	4	6	6	4	4	5	4
	4) 3,000 Hours	1	1	1	2	3	4	4	4	3	6	6	6
	5) 5,000 Hours	-	-	-	-	1	2	2	2	2	2	2	2
	6) 10,000 Hours	-	-	-	1	1	1	1	1	1	2	2	2
	7) 30,000 Hours	-	-	-	-	-	-	-	-	-	-	-	-
	8) 50,000 Hours	-	-	-	-	1	-	1	1	1	2	2	2
	9) 100,000 Hours	-	-	-	-	-	-	-	-	-	1	1	1
	Subtotal	5	5	5	19	25	19	25	25	15	20	21	20
(X)	Inherent Restraints (Cannot Detect)												
	1) Environment	-	-	-	-	-	-	-	-	-	-	-	-
	2) Loads	-	-	1	6	-	6	-	-	4	5	4	5
	3) Configuration	1	1	19	-	-	-	-	-	-	-	-	-
	Total	6	6	25	25	25	25	25	25	19	25	25	25

TABLE X. COMPARISON SUMMARY OF FIELD AND TEST PROBLEMS FOR CH-47 ROTOR CONTROLS

(Symbol)	Detection Potential	CH-47 Test Techniques							New Test Techniques	
		Whirl Test	Bench Endurance	Tie-down	Flight Test	Eglin	Yuma	Alaska	Dynamic Systems	Open Loop
(●)	Did Detect	3	7	7	6	3	-	4		
(⊕)	Could Detect with Artificial Restraints Removed									
	1) Configuration	6	3	4	6	4	7	6		
	2) Maintenance	1	1	1	-	1	1	1		
	3) Test Acceptance Criteria	2	1	4	1	3	3	3		
	4) Test Procedures	-	-	-	-	-	-	-		
(O)	Could Detect with Adequate Time									
	1) 100 Hours	-	-	-	-	2	2	2	5	5
	2) 500 Hours	-	-	-	1	-	1	1	4	4
	3) 1,000 Hours	-	-	-	4	3	4	4	4	3
	4) 3,000 Hours	1	1	1	2	2	2	1	2	2
	5) 5,000 Hours	-	-	-	1	-	1	-	1	1
	6) 10,000 Hours	-	-	-	-	-	-	-	1	-
	7) 30,000 Hours	-	-	-	-	-	-	-	-	-
	8) 50,000 Hours	-	-	-	-	-	-	-	-	-
	9) 100,000 Hours	1	1	1	1	1	1	1	1	1
	Subtotal	14	14	18	22	19	22	23	18	16
(X)	Inherent Restraints (Cannot Detect)									
	1) Environmental	2	2	1	1	-	1	-	1	1
	2) Loads	4	4	4	-	4	-	-	4	4
	3) Configuration	3	3	-	-	-	-	-	-	2
	Total	23	23	23	23	23	23	23	23	23

TABLE XI. COMPARISON SUMMARY OF FIELD AND TEST PROBLEMS FOR CH-47 ROTOR HEAD

(Symbol)	Detection Potential	CH-47 Test Techniques								New Test Techniques	
		Bearing Bench Endurance	Rotor Head CF Stop Test	Whirl Tower	Tie-down	Flight Test	Eglin	Yuma	Alaska	Dynamic Systems	Whirl Tower With Excitation
(●)	Did Detect	6	-	8	7	5	1	-	1		
(●)	Could Detect with Artificial Restraints Removed										
	1) Configuration	1	-	2	3	1	2	2	1		
	2) Maintenance	-	1	2	3	3	4	4	4		
	3) Test Acceptance Criteria	-	-	1	-	1	1	1	1		
	4) Test Procedures	-	-	3	2	2	2	2	2		
(O)	Could Detect with Adequate Time										
	1) 100 Hours	-	-	-	-	-	-	-	-	6	6
	2) 500 Hours	-	-	1	3	5	6	6	6	5	5
	3) 1,000 Hours	-	-	-	-	1	1	1	1	1	1
	4) 3,000 Hours	-	-	3	2	4	4	4	4	6	6
	5) 5,000 Hours	1	-	1	4	3	4	4	4	4	4
	6) 10,000 Hours	-	-	1	1	1	1	2	2	1	1
	7) 30,000 Hours	-	-	-	-	-	-	-	-	-	-
	8) 50,000 Hours	-	-	-	-	-	-	-	-	1	1
	9) 100,000 Hours	2	-	4	4	4	4	4	4	4	4
	Subtotal	10	1	26	29	30	30	30	30	28	28
(X)	Inherent Restraints (Cannot Detect)										
	1) Environmental	-	-	2	1	1	1	1	1	2	2
	2) Loads	-	4	3	1	-	-	-	-	1	1
	Total	10	5	31	31	31	31	31	31	31	31

TABLE XII. COMPARISON SUMMARY OF FIELD AND TEST PROBLEMS FOR CH-47 ROTOR BLADES

(Symbol)	Detection Potential	CH-47 Test Techniques						New Test Techniques	
		Whirl Tower	Tie-down	Flight Test	Eglin	Yuma	Alaska	Whirl Tower With Excitation	Dynamic Systems
(●)	Did Detect	4	8	1	3	6	4		
(⊕)	Could Detect with Artificial Restraints Removed								
	1) Configuration	7	6	7	5	6	5		
	2) Maintenance	-	-	-	-	-	-		
	3) Test Acceptance Criteria	2	1	1	1	-	1		
	4) Test Procedures	-	-	-	-	-	-		
(O)	Could Detect with Adequate Time								
	1) 100 Hours	-	-	-	-	-	-	1	1
	2) 500 Hours	-	-	1	-	-	1	2	2
	3) 1,000 Hours	-	2	9	4	6	4	5	4
	4) 3,000 Hours	1	2	2	2	1	1	4	4
	5) 5,000 Hours	-	-	-	-	-	-	1	1
	6) 10,000 Hours	-	-	-	-	-	-	1	1
	7) 30,000 Hours	2	1	2	1	3	2	2	2
	8) 50,000 Hours	-	-	-	-	-	-	-	-
	9) 100,000 Hours	1	1	2	3	3	3	3	3
	Subtotal	17	21	25	19	25	21	19	18
(X)	Inherent Restraints (Cannot Detect)								
	1) Environmental	5	1	1	4	1	5	5	5
	2) Loads	4	4	-	3	-	-	2	3
	Total	26	26	26	26	26	26	26	26

TABLE XIII. DETECTION POTENTIAL OF CH-47 TEST TECHNIQUES

CH-47 Components	Failure Mode Detection Potential (%)						
	Bench Tests			Other			
	Closed Loop						
	Without Shafting	With Shafting*	Open Loop*	Whirl Tower	Tiedown	Dynamic Systems Test*	Flight Test
Forward Transmissions	87	87	93	-	91	96	100
Aft Transmissions	96	96	98	-	98	98	98
Combining Transmissions	100	100	100	-	100	100	100
Engine Transmissions	93	93	100	-	100	100	100
Subtotal (Transmissions)	93	93	97	-	96	98	99
Drive Shafting	20	80	84	-	76	80	100
Rotor Controls	-	60**	70**	60**	78**	78**	96**
Rotor Hub	-	-	-	84**	94**	90**	97**
Rotor Blades	-	-	-	65	80	70	97
Total	-	-	-	-	91	91	98

* Test techniques not used on CH-47; effectiveness values projected by analysis.
** Back-to-back or single specimen rig.

TABLE XIV. DETECTION POTENTIAL OF HELICOPTER "A" TEST TECHNIQUES

Helicopter "A" Components	Failure Mode Detection Potential (%)							
	Bench Tests				Other			
	Closed Loop	Open Loop	Rotor Controls Rig*	Tail Rotor Whirl Stand	Whirl Tower	Tiedown	Dynamic Systems Test	Flight Test
Main Transmission	92	94	-	-	-	97	97	100
Main Rotor Hub	-	-	-	-	85	90	90	100
Main Rotor Controls	-	90	85	-	85	90	90	97
Intermediate Transmissions	-	-	-	90	-	90	90	100
Tail Rotor Transmission	-	-	-	85	-	87	87	100
Main Rotor Blades	-	-	-	-	65	80	70	98
Tail Rotor Blades	-	-	-	65	-	65	65	100
Tail Rotor Drive Shaft	-	85	-	90	-	90	90	100
Tail Rotor Hub	-	-	-	85	-	90	90	100

*Single specimen or back-to-back rig.

must be translated into test duration to permit the establishment of finite test costs. The test duration at which detectable problems actually appear is a function of the test loads and test climatic environments that are applied to the component, the hazard function of the modes, and the frequency of occurrence. These factors are examined in the following paragraphs.

Test Conditions

If the test conditions duplicate the field operations, the MTBF of the mode should be the same in the test as in the field. Accelerated testing (the application of overloads or greater cyclic rates) can increase the frequency of occurrence of the mode as seen during the test. However, for those modes whose frequencies are increased, the exact relationships between observed MTBF under accelerated test conditions and the MTBF under normal flight conditions are not completely understood at the present time. If anything, accelerated testing has historically produced failure modes or rates that have been dismissed as legitimate problems because of the implied lack of validity of the test conditions. Accelerated testing in the order of 110 to 120 percent of power, speed, or thrust (as recommended in Reference 3) may not create these interpretation problems, but also may not significantly reduce test duration requirements on test techniques which are testing a whole assembly. Thus, in this study, test conditions are assumed which do not significantly alter the MTBF's in the test from those in the field. This is an uncomfortable position and suggests somewhat of a "brute force" approach to testing, but one that is dictated by the realities of existing technology.

Time Dependency (Hazard Function)

Failure rates that increase with component time cause the rate of problems appearing to increase with test duration. Based on CH-47 experience, very few modes have a clearly increasing failure rate. Constant failure rates have therefore been assumed in this study.

MTBF (Mean Time Between Failures) Off the Board

Based on realistic test conditions and a constant failure rate, the MTBF of each failure mode as predicted off the board will determine the test duration required to detect that problem. When the test duration is equal to the MTBF (assuming a constant failure rate), there is a 63 percent probability that the mode will have been detected. When test duration is twice that of the MTBF, the probability goes to 87 percent.

Test Duration (Sizing)

The method of sizing problem identification test costs will be to vary the durations of test techniques in order to detect and correct sufficient failure modes so that the net effect of the remaining modes equals the required MTBR of the assembly. Corrective action is considered to have taken place when the problem has been detected twice (test duration equals twice the MTBF). This assumption is not significantly compromised by the preceding probabilistic discussion, since, in the process of detecting a few infrequent modes, sufficient operating time is accrued to observe multiple failures of most modes and to verify the necessary corrective action.

Using this approach, along with the off-the-board MTBR for each component and the effectiveness percentages for each test technique, test durations were calculated for various required MTBR's. Anticipating the test programs to be traded in subsequent sections, required MTBR vs test duration plots were prepared for individual test techniques and mixes of test techniques. Figure 21 shows a sample of these plots for the main transmission. As can be seen, the low percentage of effectiveness for the bench test prevents the main transmission from achieving the required MTBR that could demonstrate a 500-hour MTBR*, even at the 30 percent confidence level. The dynamic systems test does slightly better, since it has a slightly higher degree of effectiveness.

Consequently, each component then has a set of required MTBR/test-duration relationships (similar to those shown on Figure 21 for the main transmission).

These expressions of effectiveness allow evaluation of candidate test programs by the use of various test techniques and the testing of a variety of components.

To illustrate the effect of the relative complexity of the various components (as expressed in the off-the-board MTBR), the relationship of the required MTBR and the duration has been shown for each component for a 100 percent effectiveness test technique. Figure 22 illustrates this relationship for the drive system components, and Figure 23 for the rotor components. On each plot, the effect of increasing complexity is evident, since each component has a different required MTBR for an equal test duration.

NOTE: It must be emphasized that the use of the effectiveness values on Table XIV assumes that all artificial restraints have been eliminated. This is considered a reasonable assumption for future test programs where the requirement for a contractual demonstration causes the formulation and operation of problem identification

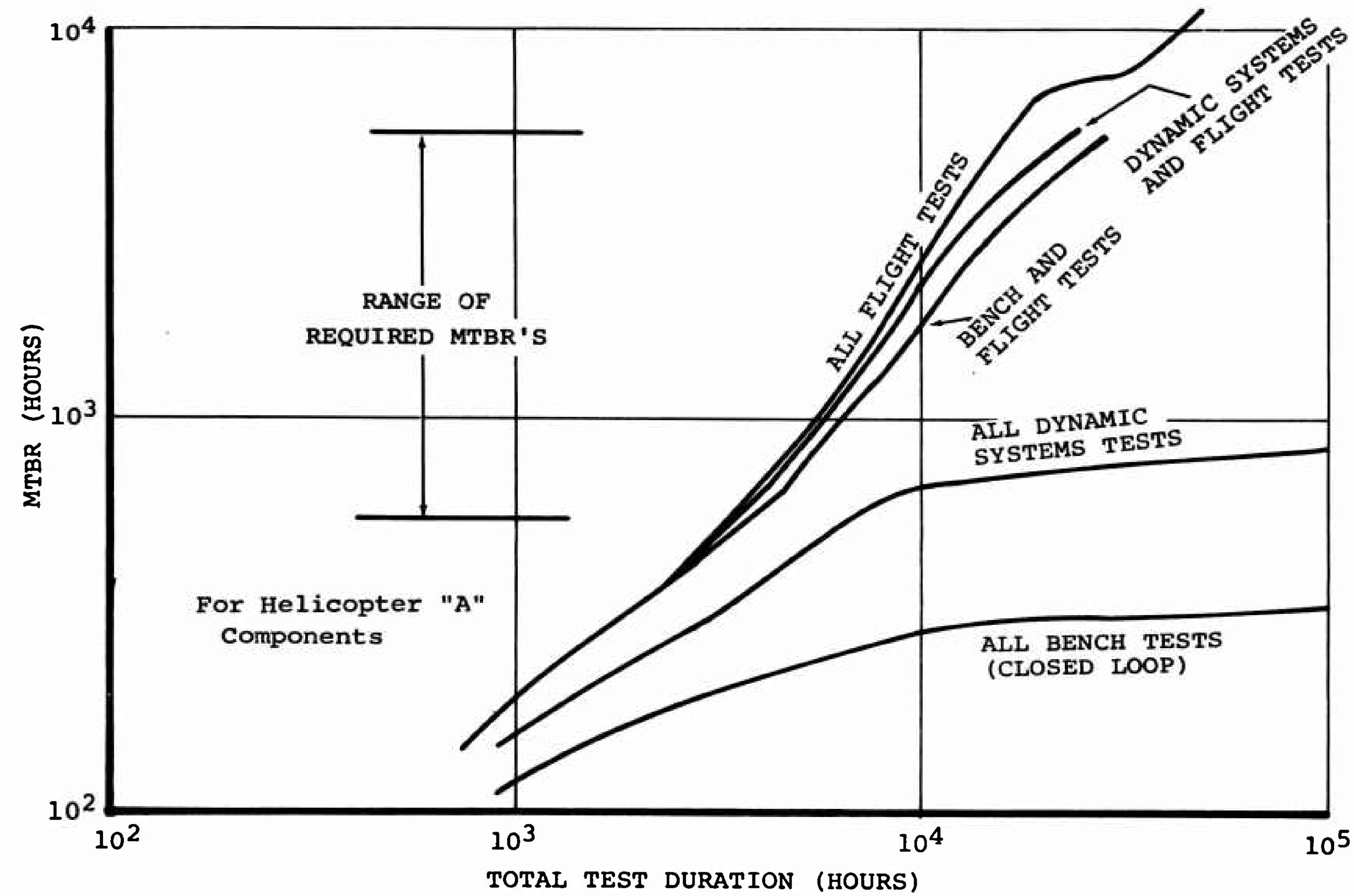


Figure 21. Growth of Main Transmission MTBR with Test Duration.

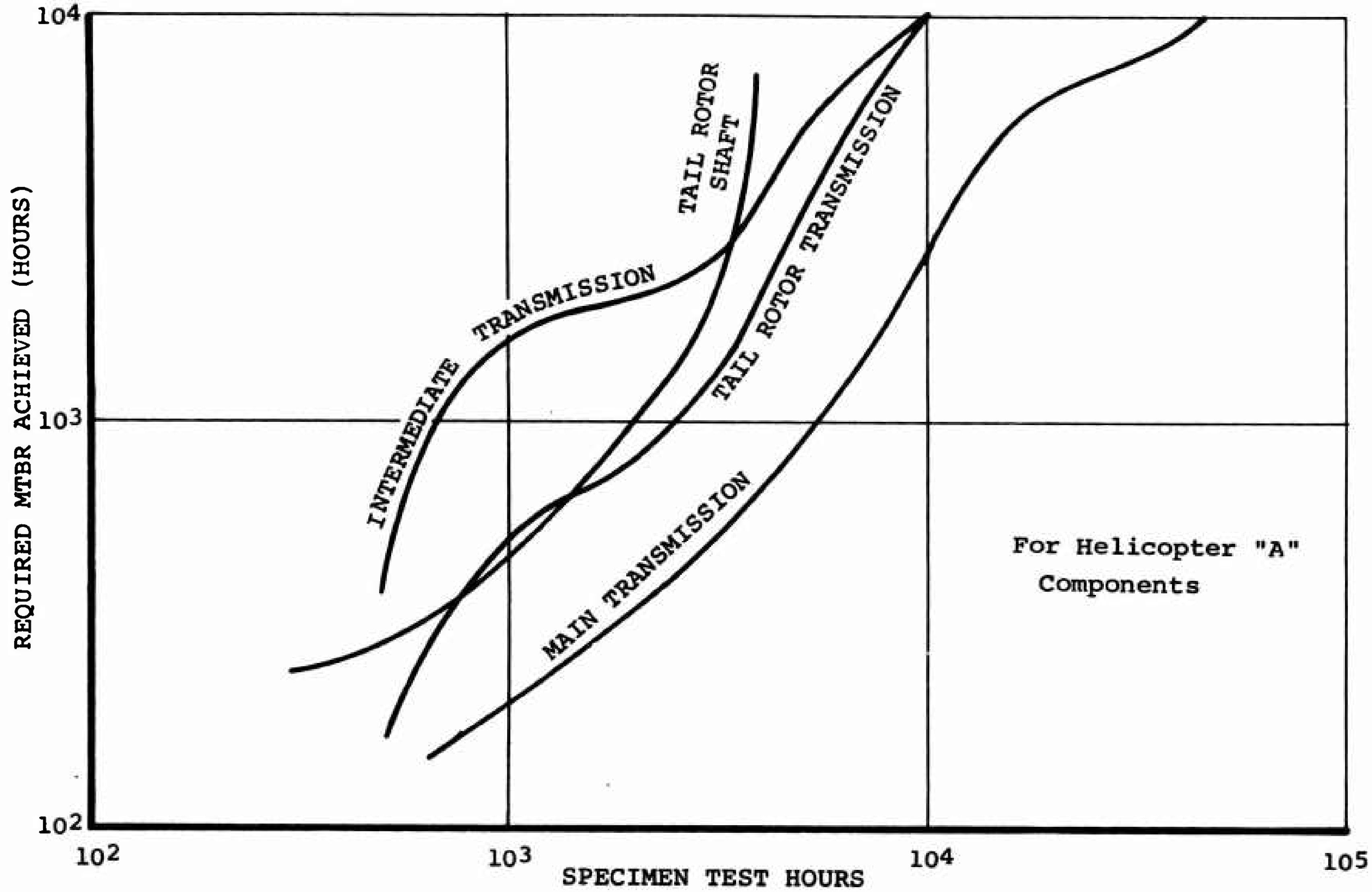


Figure 22. Effect of Test Duration on MTBR Achieved for Drive Components (100% Effectiveness Flight Test).

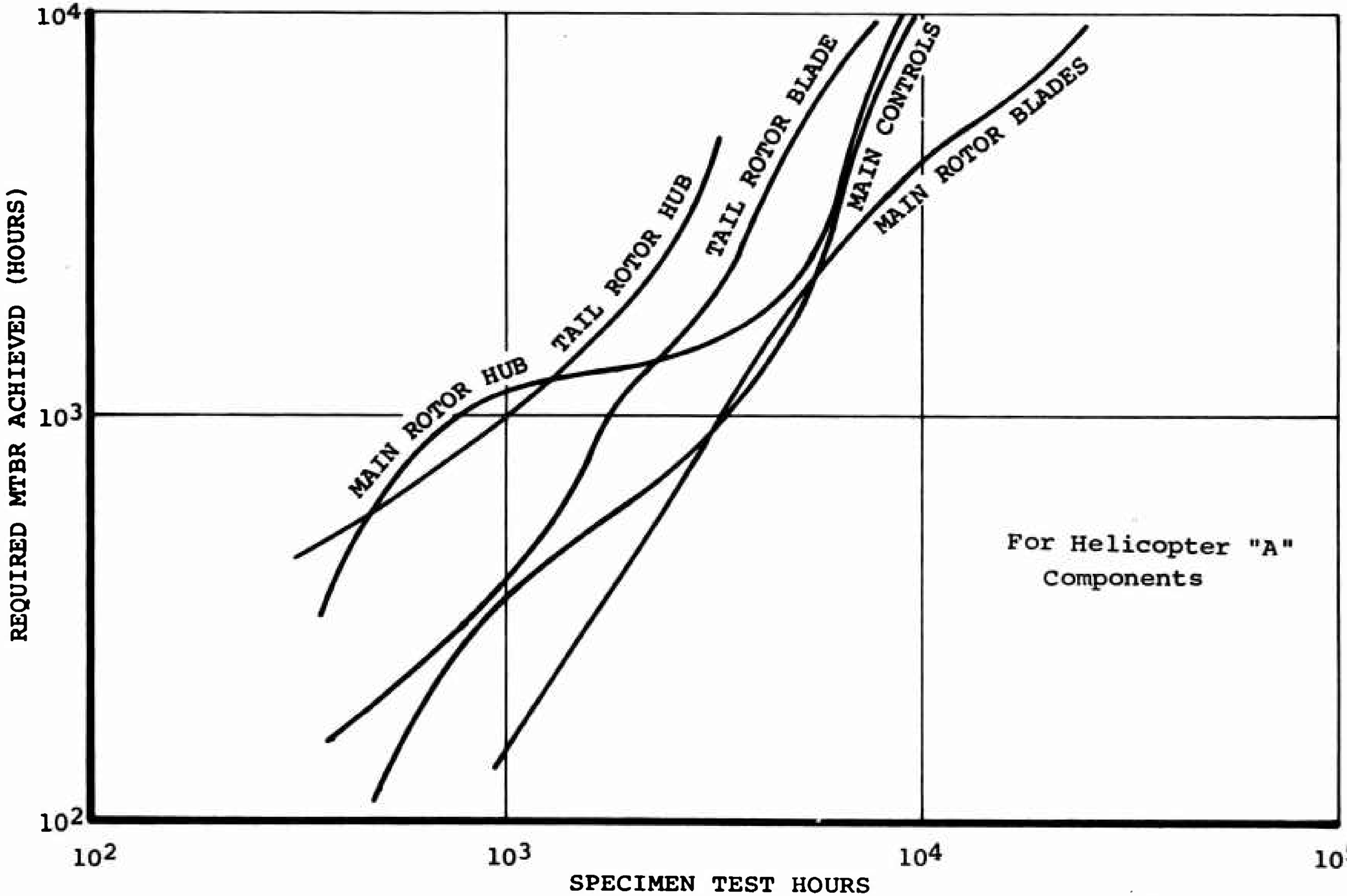


Figure 23. Effect of Test Duration on MTBR Achieved for Rotor Components (100% Effectiveness Flight Test).

tests to be significantly more rigorous in elimination of restraints.

TEST TECHNIQUE COSTS

The estimated costs of various test techniques are calculated considering both nonrecurring and recurring cost elements. The costs that are calculated for this study include the following:

Nonrecurring

1. Fixture Costs: considers the design, manufacture or procurement, and installation of the fixture.

2. Specimen Costs: considers the procurement of a number of test specimens (exact number for each test technique noted elsewhere).

3. Preparation of Test Procedures and Final Test Report: considers engineering man-hours.

4. Setup and Instrumentation: considers labor and material.

Recurring

1. Power Operating Costs: considers the costs of fuel or electricity used to drive the test stand.

2. Support Costs: considers engineering and shop labor required to operate and maintain the fixtures and specimens.

The cost estimates for test techniques used on the CH-47 or considered applicable to the test programs of Helicopters "A" and "B" are displayed on Table XV.

NOTE: Costs are displayed on the CH-47 for size, weight, and configuration comparison purposes only. Costs are displayed for Helicopter "A" in order to perform the trade-off studies and for preparation of the total costs of the Helicopter "A" Sample Plan. Costs for Helicopter "B" are displayed to cost the helicopter's Sample Plan for comparison purposes.

The values on Table XV have been generated using the maximum amount of historical data possible. However, it should be emphasized that the cost estimates for any specific test program can differ from the values shown, due to individual program considerations. The key ground rules that were utilized in the generation of these values are shown on Table XVI.

TABLE XV. SUMMARY OF TEST TECHNIQUE COSTS AND SCHEDULES

Technique	Costs: CH-47		Costs: Helicopter "A"		Costs: Helicopter "B"		Schedules: CH-47 Lead Time (mo)	Schedules: CH-47 Oper. Rate (hr/mo)	Schedules: Helicopter "A" Lead Time (mo)	Schedules: Helicopter "A" Oper. Rate (hr/mo)	Schedules: Helicopter "B" Lead Time (mo)	Schedules: Helicopter "B" Oper. Rate (hr/mo)
Type I	($ million)		($ million)		($ million)		(Detailed schedules are not required to derive Type I ground test costs.)					
Fatigue Rotor Components	3.46	6.12	3.06	5.45	4.19	9.16						
Fatigue Control Components	0.76		0 67		0.93							
Fatigue Drive Components	1 56		1.10		3.10							
Static Load	0.34		0.31		0.46							
Miscellaneous (Gear Resonance, etc.)	0.35		0 31		0 48							
Flight	26.40 (1,700 flight hours)		20.30 (1,500 flight hours)		39.00 (1,500 flight hours)		26	8	24	20	26	20
Type II	Non-recurring ($1000)	Recurring ($/hr)	Non-recurring ($1000)	Recurring ($/hr)	Non-recurring ($1000)	Recurring ($/hr)						
Controls Bench Back-to-Back	44	37	94	41	211	51	6	500	6	500	6	500
Controls Bench Single Specimen	44	37	74	37	166	46	-	500	6	500	6	500
Tiedown	4,190	2,200	2,300 (mod 2,100)	1,700	-	-	24	165	24 (24)	165	-	-
Dynamic Systems Test	N/A	N/A	2,020	580	-	-	N/A	N/A	20	200	-	-
Whirl Tower	3,430	650	2,580 (mod 560)	220	6,187	326	16	350	20 (20)	350	22	350
Hub Bearing	24	16	N/A	N/A	144	49	6	500	N/A	N/A	9	400
Transmission Open Loop	-	-	2,284 (mod 480)	354	-	-	-	-	21 (18)	350	-	-
Tail Rotor Whirl Tower	N/A	N/A	330	110	N/A	N/A	N/A	N/A	16	400	N/A	N/A
Alaska Climatic	-	900	-	2,500	-	4,630	-	8	-	20	-	20
Yuma Climatic	-	1,508	-	2,500	-	4,630	-	8	-	20	-	20
Flight	N/A	N/A	-	2,500	-	4,630	N/A	N/A	24	70	26	70
Type IV												
Flight (Development Phase)	-	-	-	2,500	-	-	-	-	N/A	50	-	40
Flight (Operational Phase)	-	-	-	200	-	200	-	-	N/A	50	-	40

TABLE XVI. COST VARIABLES AND STUDY ASSUMPTIONS

Cost Variable	Study Assumption
Nonrecurring Costs	
Modification of equipment existing and available, or purchasing of used or new equipment	For Helicopter "A", new equipment has been assumed for the controls bench, dynamic systems, transmission closed loop, and the tail rotor whirl tower. Modification of available existing equipment was assumed for one tiedown, two main rotor whirl towers and one transmission open loop. Universal fatigue machines and static load machines are assumed available. For Helicopter "B" Type II tests, new equipment has been assumed for all test techniques.
Amount of overhead (burden) applied to base rates	Consistent burden has been applied commensurate with industry averages for 1970. Profit is not included. (Costs of the CH-47 climatic tests are Government furnished data.)
Test location	All tests are assumed performed at the contractor's facility (except Alaska and Yuma climatic tests).
Make-or-buy decision	The purchase of commercially available equipment and the manufacture of equipment not commercially available has been assumed.
Assignment of cost for equipment with developmental and production usage	The total cost of equipment has been assigned to the developmental program.
Land, buildings, power substations, lights, instrumentation	These items are not included in the test costs except as appropriate for the whirl tower. However, instrumentation transducers, failure detectors, wire and calibration are included.

TABLE XVI - Continued

Cost Variable	Study Assumption
<u>Nonrecurring Costs</u>	
Overload requirements	A fixture overload capability of 25 percent has been assumed for power, speed, and load on Type II tests.
Specimen cost and availability	The cost of the aircraft has been included in the tiedown. Flight aircraft are costed by including IROAN costs as a recurring element. Sufficient quantity of specimens is included to successfully meet the schedule requirements, with overhaul of the specimens.
<u>Recurring Costs</u>	
Instrumentation quantity	Reasonable quantity of instrumentation based on the CH-47 is assumed.
Electrical and POL costs	Electrical costs above the Boeing baseline requirements, and POL costs, are included.
Shift operation	A 3-shift workday and a 7-day work week operation is assumed to minimize expense.
Specimen overhaul and maintenance of the test setup	Recurring costs have been assumed for specimen overhaul and maintenance of the test setup.
Interruptions of developmental program to perform production functions	No interruptions are assumed.

In summary, the ground rules on Table XVI are generally chosen to generate representative costs for the average contractor performing the tests on Helicopter "A" or "B". The costs are baseline values; i.e., no undue circumstances such as massive program delays are assumed. This philosophy is consistent with that assumed in the effectiveness area. Also, the costs provided are contractor costs, and do not include normal contractor profit. This reflects the fact that future contractual demonstration will probably involve economic incentives and penalties, with profit becoming a dependent variable of contractor performance.

TEST TECHNIQUE SCHEDULES

The schedules for various test techniques are defined by two distinct characteristics. The first is the lead time necessary from the go-ahead decision to the point where the test fixture is available for operation. The second characteristic is the quantity of test hours that can be accumulated in a given calendar period. This has been termed the operational rate. These factors are extremely important in determining the costs of test programs, since they ultimately determine the number of test rigs required to fulfill a given test duration in a given calendar period.

The schedule characteristics for the Helicopter "A" and "B" candidate test techniques (Table XV) were derived through a process similar to that used in determining effectiveness and costs. That is, historical data on the CH-47 were reviewed and adjustments were made to reflect certain assumptions:

1. All tests are operated for 3 shifts each day, 7 days a week.
2. There are no interruptions in developmental tests for production usage of the test facility.
3. Additional specimens are available to immediately replace test specimens which have failed or require removal.
4. Fixture reliability is representative of mature equipment.
5. Lead times to procure fixtures assume a degree of preimplementation that is traditional in aircraft programs. That is, basic conceptual and sizing efforts are completed, but detail design must await contract go-ahead.

5. PROBLEM IDENTIFICATION TEST PROGRAM TRADES

TRADE GROUND RULES

The trade-off procedures and the display of the results are designed to answer three related questions:

1. What is the optimum mix of test techniques?
2. What are the costs of increasing levels of required MTBR?
3. What is the cost impact of varying program elapsed times?

The trade-off studies were structured tc simultaneously answer these three questions for Helicopter "A".

There are three groups of trade-off studies (the first two groups could more correctly be called initial selections). In the first group, alternate test techniques which test the same components and have equal effectiveness are compared from a cost standpoint. Two selections were performed in this group:

1. Tiedown vs dynamic systems test (DST)
2. Single specimen vs back-to-back rotor controls rig

The second group of trades involves evaluation of alternate test techniques that test the same components but have different effectiveness and schedule characteristics. There is only one selection in this group: open loop vs closed loop transmission test.

The test techniques that survived these selections were then arranged into various test programs for subsequent trade-off. In each candidate test program, all components of the dynamic system were tested by one or more test techniques. Each complete test program was sized to achieve various levels of required MTBR, and costed accordingly. In this group, the dynamics of accumulating test hours (cost) and adding test rigs (cost) are reflected when a specific elapsed time is considered. Comparison of the costs of each test program to achieve an equivalent MTBR is the evaluation parameter.

INITIAL SELECTIONS (FIRST GROUP)

Dynamic System Test Vs Tiedown

The dynamic system test (DST) (described in Appendix VI) is much like the traditional tiedown aircraft. Tables XIII and XIV show that the effectiveness values for these two techniques are approximately the same. The lead time and operational rate values favor the DST because of the greater complexity of the complete aircraft (tiedown). Although the cost advantage of the DST (Figure 24) depends on the amount of existing facilities that are assumed, the DST is always less expensive. However, this comparison overlooks the fact that the tiedown aircraft, as a test technique, can test aircraft subsystems other than the major dynamic systems. If only the major dynamic system components are considered, the DST is the preferred test technique and will be considered as a candidate test technique in subsequent trades.

Single Specimen Vs Back-to-Back Rotor Controls Rig

These alternates have exactly the same effectiveness values since the test techniques are essentially similar, although the back-to-back rig tests two specimens at the same time. Because of this, the operation costs per specimen hour on the back-to-back rig are slightly more than half those of the single specimen rig (Figure 25). However, because of the additional specimen, the initial (nonrecurring) costs of the back-to-back rig are somewhat higher. This creates a cost crossover point at 1000 hours' test duration for Helicopter "A". Since most candidate test programs test this component for longer durations, the back-to-back rig costs and schedules are used in subsequent trades. This trade is somewhat different for Helicopter "B" (Figure 26) where higher costs of the specimens move the cost crossover point out to 2500 hours' test duration. This is very near the requirement for the Helicopter "B" sample plan. In this case, the back-to-back rig is preferred from a scheduling standpoint and is used to cost the Helicopter "B" plan.

INITIAL SELECTIONS (SECOND GROUP)

Open Loop Vs Closed Loop Transmission Test

In this selection, the open loop has slightly higher values of effectiveness (Tables XIII and XIV) and therefore requires less operating time than the closed loop to achieve an equal required MTBR. Cost and schedule comparisons depend on whether an existing open loop is modified or a completely new fixture is required. This data is shown in Table XV and is summarized on Figure 27.

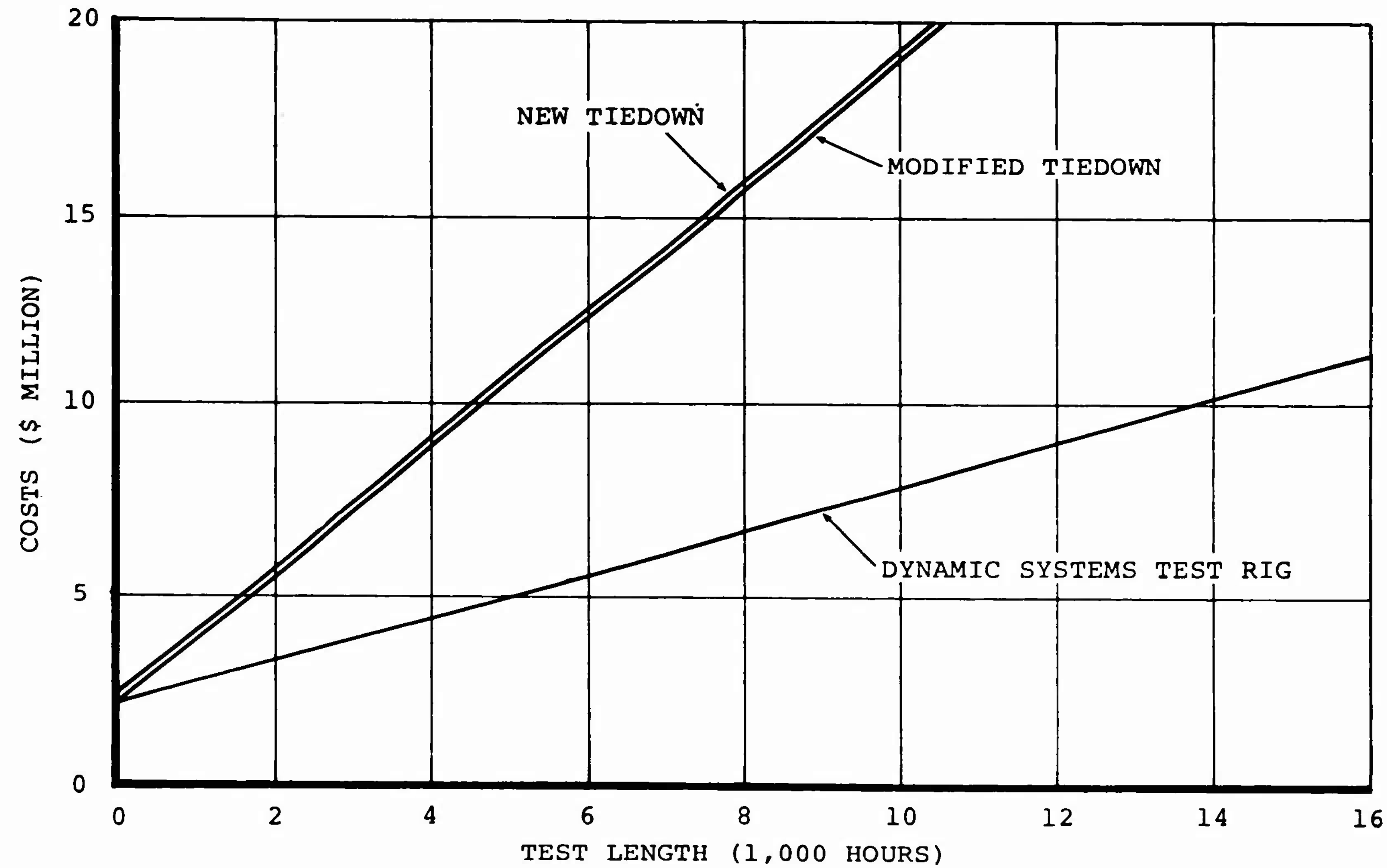


Figure 24. Tiedown and Dynamic Systems Test Rig Costs for Helicopter "A".

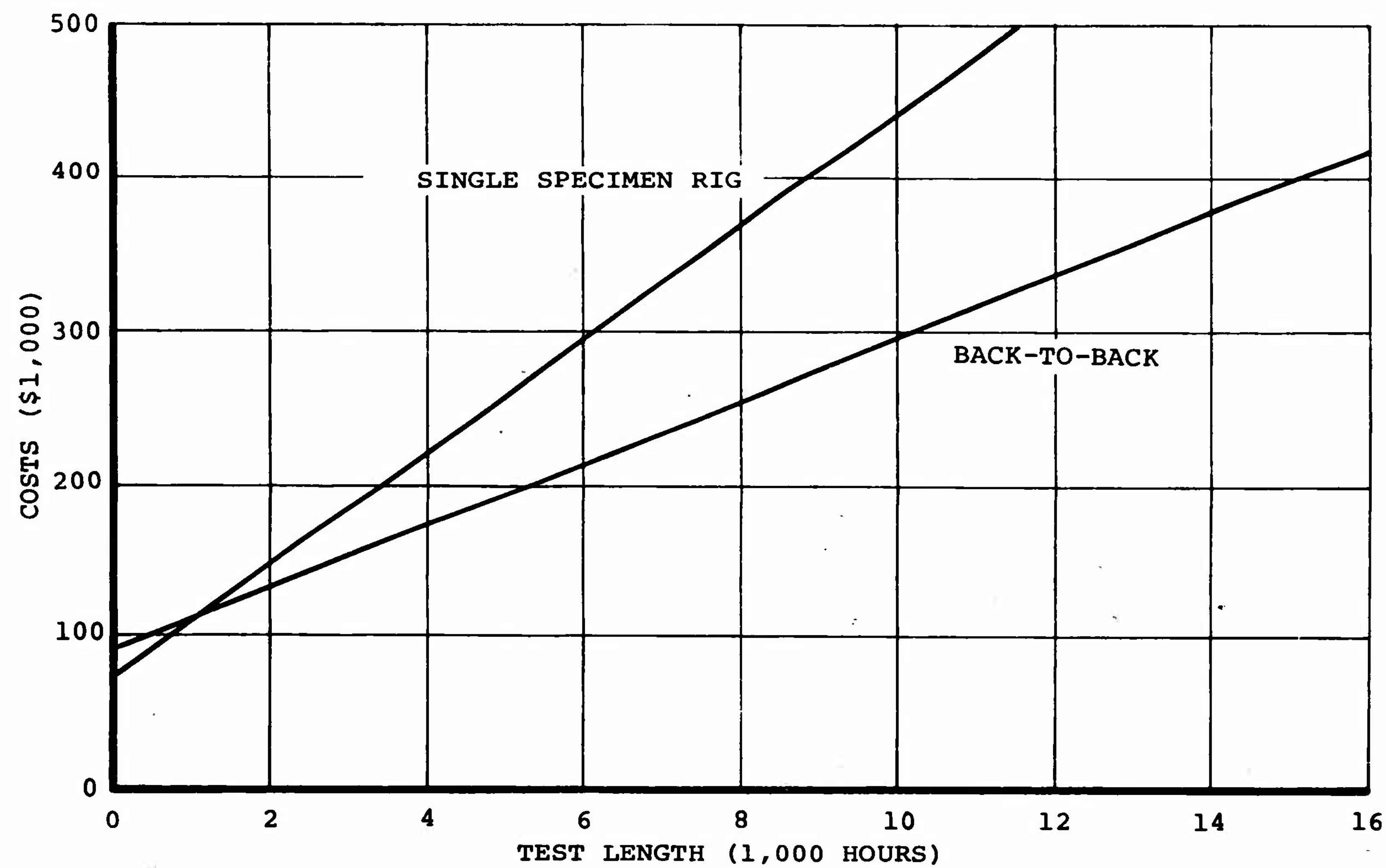


Figure 25. Upper Controls Bench Test Costs for Helicopter "A".

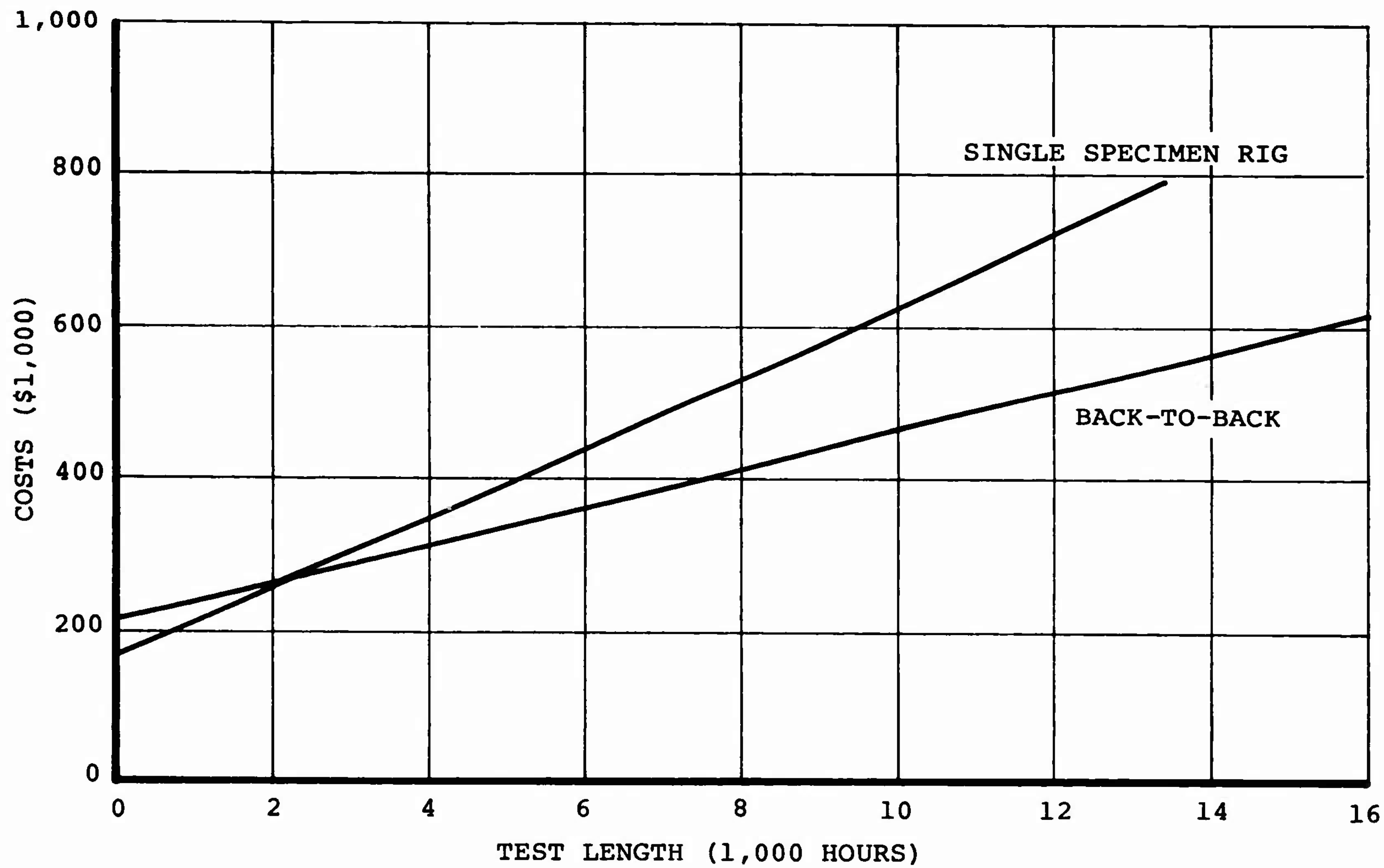


Figure 26. Upper Controls Endurance Costs for Helicopter "B".

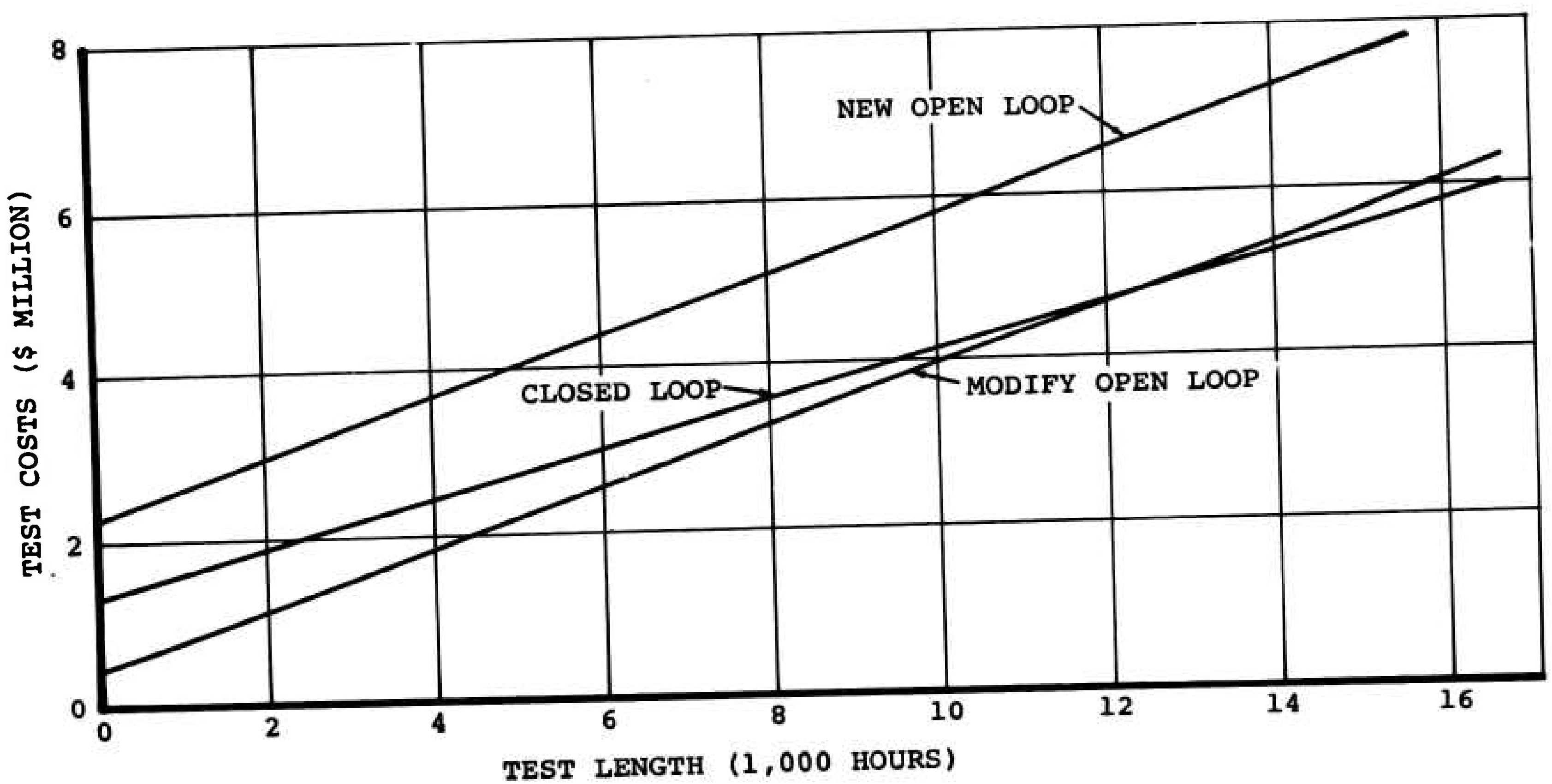


Figure 27. Main Transmission Bench Test Costs for Helicopter "A".

Using these differences in costs, schedules, and effectiveness, total costs of open and closed loop tests have been calculated for a range of required MTBR values extending from 600 to 5000 hours. These costs are displayed on Figure 28 and clearly indicate that if the contractor has an existing open loop facility available for modification, modification of the facility will yield the most economical technique up to 12,000-hour duration. However, since the existence of an adaptable open loop stand is not typical of the industry, this alternative was not used for the study. For the remaining alternatives of a new open loop or a new closed loop, Figure 28 indicates that the closed loop is the more economical for a given required MTBR, and it has therefore been used for structuring candidate programs.

TEST PROGRAM TRADES

Eight candidate test programs were configured, each testing all components of the dynamic system, and each using one or more individual test techniques. Those techniques that did not survive the two selection processes were not further considered. The mixed test technique programs investigated were:

1. All flight test
2. Dynamic system test and flight test
3. Dynamic system test, transmission closed loop, and flight test
4. Dynamic system test, transmission closed loop and swashplate rig, and flight test
5. Dynamic system test, transmission closed loop, swashplate rig and whirl tower, and flight test
6. All bench (transmission closed loop, swashplate rig, whirl tower and tail rotor stand) and flight test
7. All bench test
8. All dynamic system test

Of the candidate test programs enumerated, programs 7 and 8 did not have any flight test and therefore had severe limitations in the level of MTBR that could be achieved (as discussed in Section 4 and illustrated in Figure 21). For this reason, they cannot be considered viable test programs.

NOTES:
1) HELICOPTER "A" 3-YEAR PROGRAM
2) MTBR REFLECTS EQUAL NUMBER OF FLIGHT TEST HOURS FOR EACH BENCH TEST TECHNIQUE

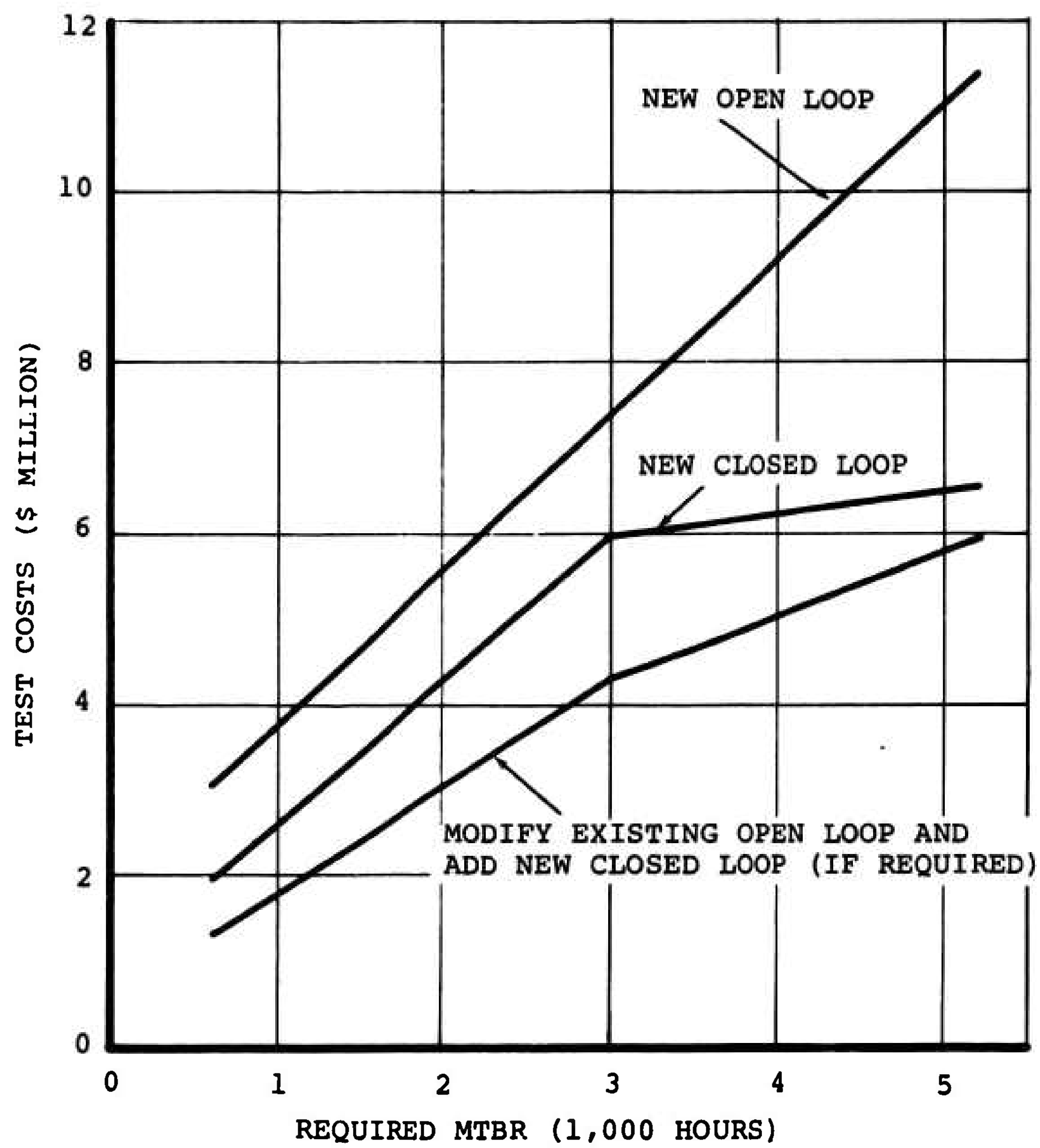


Figure 28. Main Transmission Bench Test Costs for Required MTBR's.

Programs 3, 4 and 5 were found to represent gradations in costs between programs 2 and 6. This was anticipated, since they are actually compromises between a single test technique testing all components and a collection of test techniques each testing one component only. The cost differences between programs 2 and 6 were surprisingly small. For this reason, it was decided that only programs 2 and 6 would be shown. For comparison, it was considered imperative that an all-flight-test program also be shown.

The costs to achieve various levels of MTBR were developed for the following candidate programs:

1. Bench plus flight test (A)

2. A dynamic system test plus flight test (B)

3. An all-flight-test program (C)

Each program was constructed for time periods of 3 years, 4 years, and 6 years.

As determined in Section 4, required MTBR levels up to 5200 hours were necessary out of the Type II testing; the range of required MTBR to be investigated was therefore defined.

The costs for each program were calculated at several required MTBR values. Each calculation was performed on a separate worksheet, included as Appendix IV. The costs were plotted on Figures 29, 30, and 31 representing 3-, 4-, and 6-year programs, respectively.

For subsequent use, an average cost line was drawn midway between test programs A and B. This curve will be used later for combining problem identification test program costs and demonstration costs.

RESULTS OF TRADE-OFF STUDIES

In calculating the costs for each of the required MTBR points for the test programs, two considerations requiring discussion became apparent:

1. The component required MTBR values resulting from a given test program as they relate to the minimum required MTBR value for each component

2. The amount of flight test required to supplement each ground test program

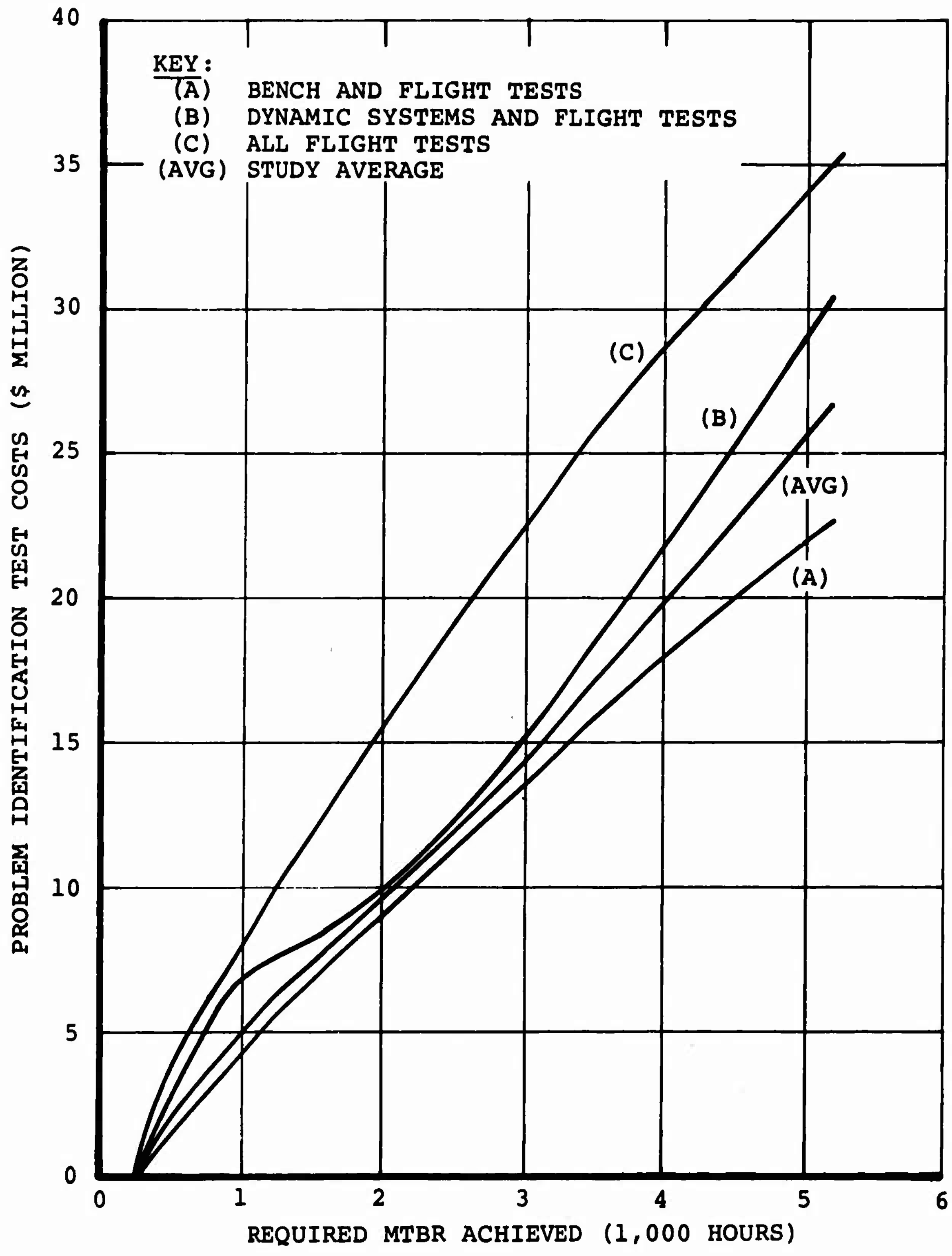


Figure 29. 3-Year Program Problem Identification Test Costs for Required MTBR's.

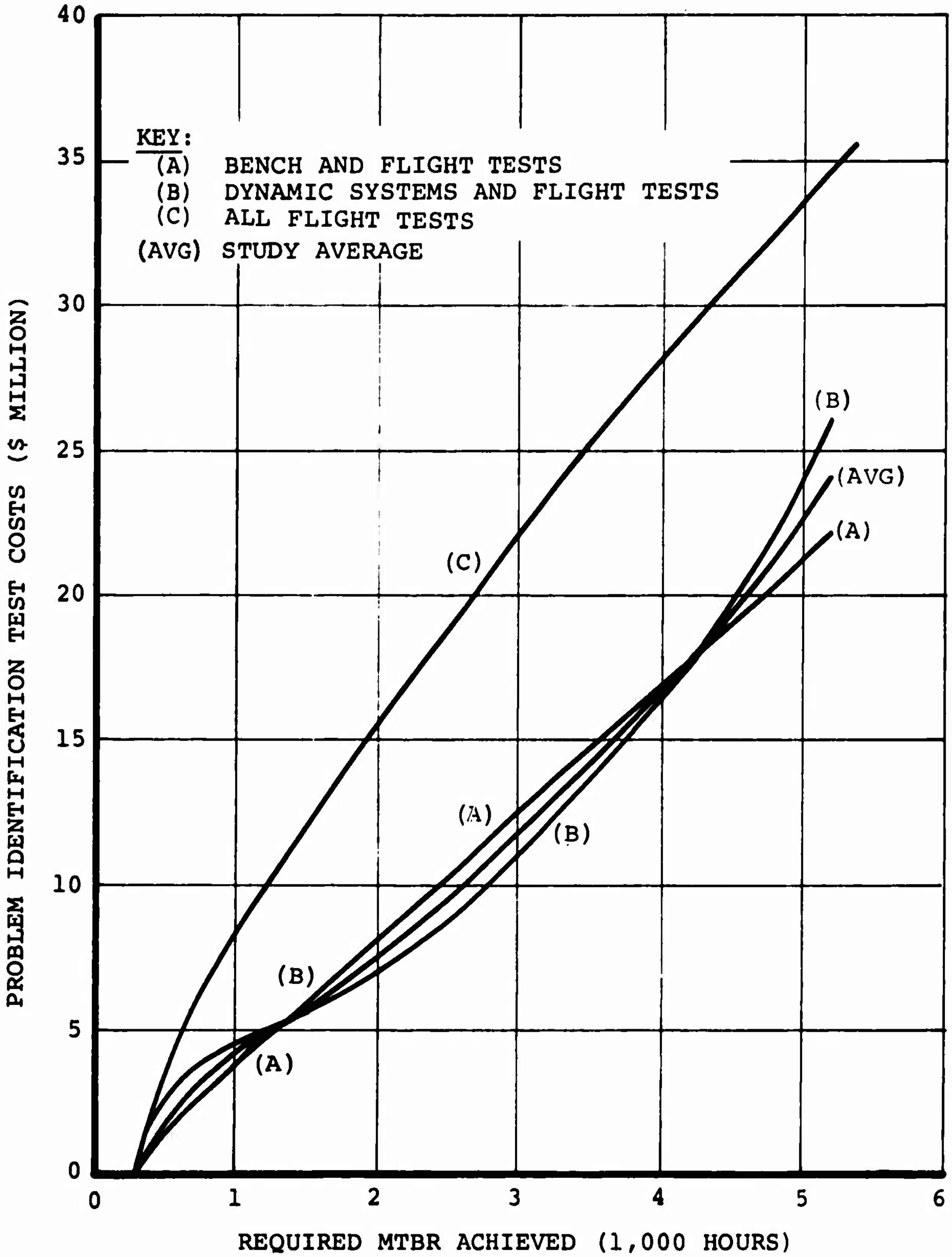


Figure 30. 4-Year Program Problem Identification Test Costs for Required MTBR's.

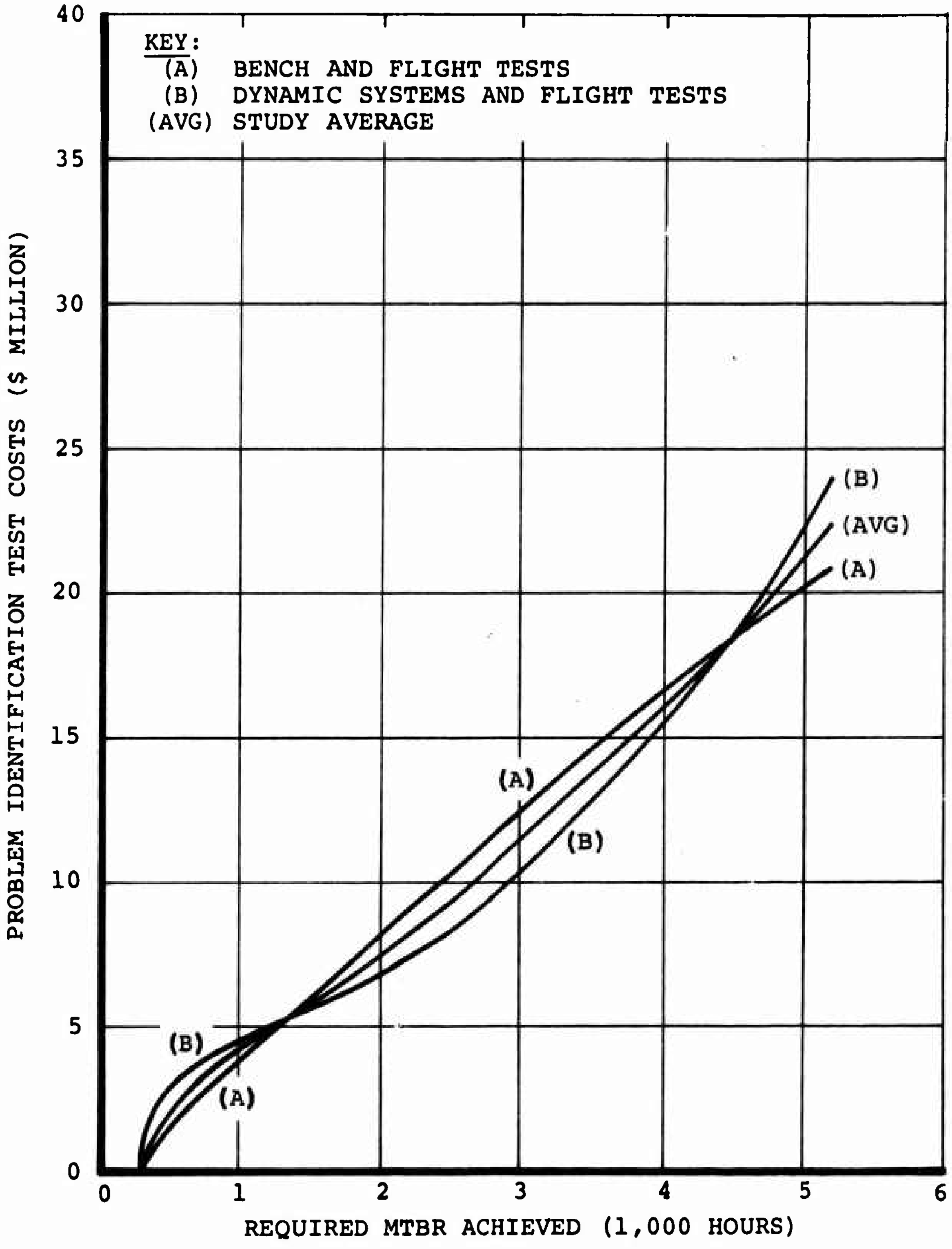


Figure 31. 6-Year Program Problem Identification Test Costs for Required MTBR's.

Required MTBR Values

In sizing each test program to achieve a specific required MTBR value, the durations of individual test techniques were varied to discrete values. In reality, certain test techniques test several components which may have had different off-the-board MTBR's. Consequently, an equal test duration applied to each component would produce unequal MTBR outputs. Because of this, the individual test technique had to be operated to a duration where the lowest component MTBR output was equal to the required MTBR for the program. This meant that all other "more reliable" components being tested by that test technique were overtested (and overdeveloped) in the sense that they achieved an MTBR output which was higher than that required. The worksheet in Figure 87 represents a bench plus flight test program, sized for a 3000-hour required MTBR. As can be seen from the worksheet, the tail rotor stand is operated for 2800 hours. The component driving the test duration is the tail rotor transmission whose MTBR output is at 3000 hours. Meanwhile, the intermediate transmission achieves an output (required MTBR) of 5300 hours, well above the 3000-hour program requirement. The overtest phenomenon increases at higher values of required MTBR and is particularly acute on the dynamic system test program, where all components are tested at once, the test duration for the entire rig is paced by the most unrealiable component, and all other components are overtested. This factor increases dynamic system test program costs over the bench test programs and provides a distorted comparison.

An alternative method of displaying the costs of the candidate test programs which were structured is to consider a weighted average of the MTBR values achieved on each component. Under this system, the weighting of the MTBR for each component is proportional to the costs incurred as a result of a removal. Thus, this weighted-average MTBR describes the worth of the test program more accurately since it reflects the downstream logistics costs. The costs of the test programs are plotted against the weighted average MTBR on Figure 32 as well as the nonweighted DST and bench-oriented program cost curves from Figure 29.

It is evident from Figure 32 that the apparent cost advantage of the bench-oriented programs as suggested on Figure 29 is largely diluted at most MTBR levels.

However, formal contractual demonstration programs in the near future will probably be arranged to verify a single MTBR value on all components as opposed to various MTBR values. Therefore, the cost/reliability relationships shown in Figures 29, 30, and 31 are considered appropriate.

Flight Test

The limitations of various types of ground tests in terms of their ability to produce the necessary required MTBR's were discussed in Section 4 and illustrated in Figure 21. For most reasonable levels of MTBR, it becomes necessary to supplement the ground testing with flight testing. Obviously, the amount of flight testing performed affects the amount of ground testing that is required.

The method for determining the amount of required flight testing must acknowledge that a certain amount of flight testing is performed for program requirements unrelated to reliability. Specifically, tests for stability, performance, structural demonstration, stress and motion, etc., are requirements that will be met through a flight test program, without regard to the MTBR objectives. Cost of this testing is therefore classified as Type I test cost. This flying can contribute to reliability improvement, with virtually no cost increment against Type II costs. The amount of flight testing performed for Type I purposes will be fixed for Helicopter "A" at 1500 flying hours. The derivation of this value is discussed in Section 7. Any additional flight testing required beyond this 1500 hours of Type I flight is costed completely against Type II funds.

Increments of flight testing should be realistically considered as an alternate to increments of ground testing. Accordingly, the distribution of ground test hours and flight test hours is calculated by determining the minimum cost combination. This optimization considers that as the more costly (but more effective) flight testing is increased, the amount of less costly (but less effective) ground testing decreases. The point where the sum of flight and test costs is at a minimum represents the optimum. The flight test hours determined in this process, and consequently used in the trade studies, are summarized on Figure 33. Assuming a delivery capability of three aircraft per month, the aircraft operational rates shown on Table XV are within reasonable limits of factory production.

TRADE-OFF CONCLUSIONS

The trades were designed to explore the effect on problem identification of: the mix of test techniques used in the test program, variations in required MTBR, and the elapsed time of the test program. The conclusions reached concerning these issues are presented in the following paragraphs.

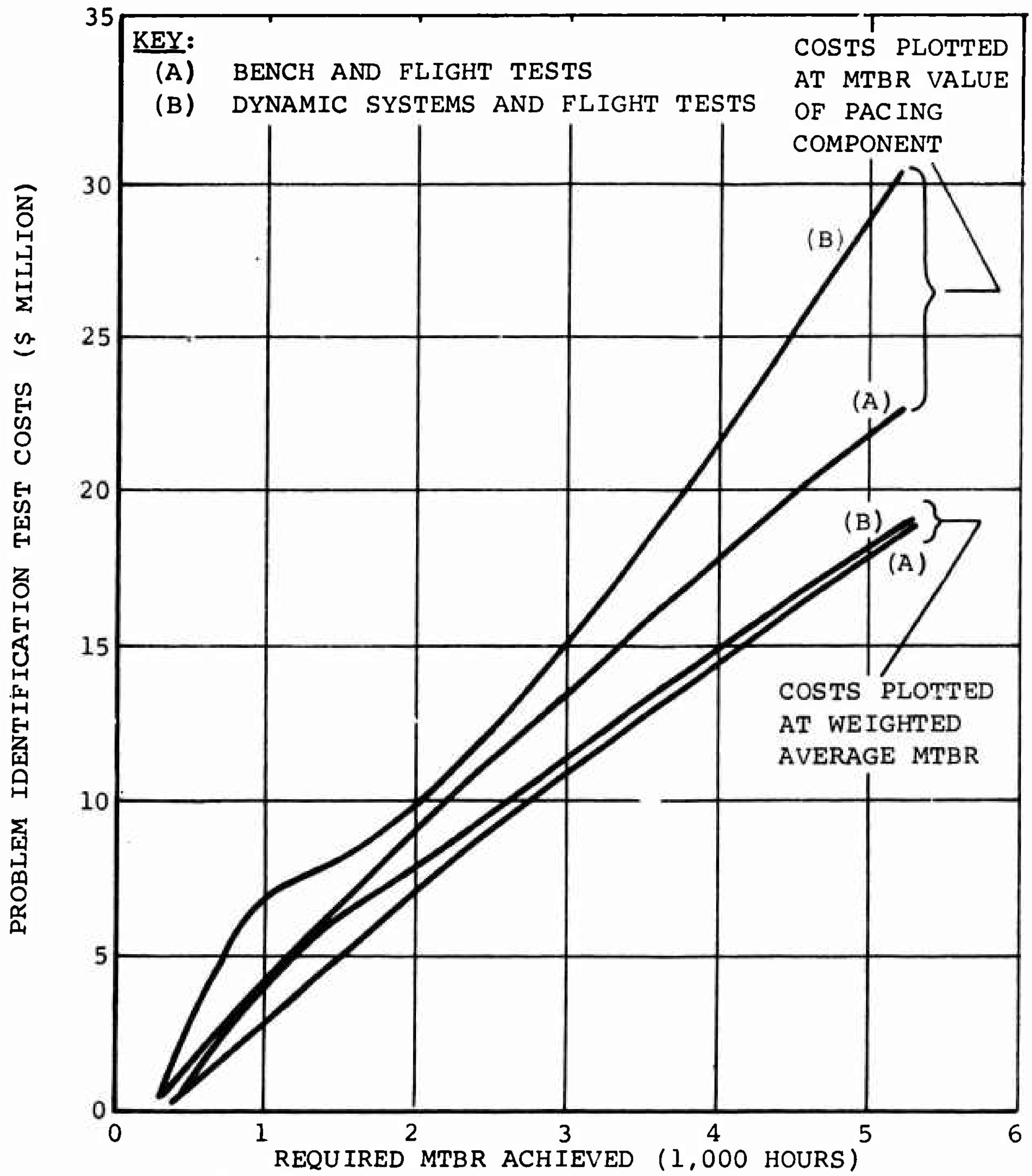


Figure 32. 3-Year Program Problem Identification Test Costs for Required MTBR's - Weighted and Nonweighted MTBR's.

Mix of Test Techniques

1. Determination of the optimum mix of test techniques depends upon the required MTBR of each component. If a minimum required MTBR value is desired for any component, a mix of bench and flight tests appears to be the most economical at higher values of MTBR. Programs which test many components for equally high durations have a tendency to overtest some components. If the worth of this overtesting is acknowledged (see Figure 32), there is no apparent cost advantage to bench-type programs.

2. Use of Type I flight testing for reliability problem identification gives bench-type tests a cost advantage at lower values of MTBR. This happens because Type I flight testing is "free" (i.e., no Type II cost penalty) and is added as a fixed value (1500 hours in this study) to the bench-type program. Since this produces sufficient effectiveness, lower costs of bench-type tests offset the higher effectiveness of the dynamic systems test.

3. As the elapsed time available for testing becomes shorter, cost advantages of bench-type programs over dynamic systems test programs become still greater.

4. Flight testing should be used to supplement the ground tests (either bench or dynamic systems). This should occur for longer durations and be more closely monitored than in past helicopter programs.

5. The availability of existing test fixtures that can be modified for use in a test program can significantly affect the choice of test techniques, particularly among alternative bench tests.

6. Where only the major dynamic components are being considered, dynamic systems tests have a clear advantage over tiedown tests.

Required MTBR Levels

1. Greater cost variations result from differences in required MTBR's than from variations in test techniques.

2. The potential variations in test costs caused by differences in management and operating procedures far surpass variations caused by test techniques. With the predicted off-the-board MTBR's, test costs could be 8 to 10 times those shown if artificial restraints are not removed, corrective actions is delayed, or test schedules are not fulfilled.

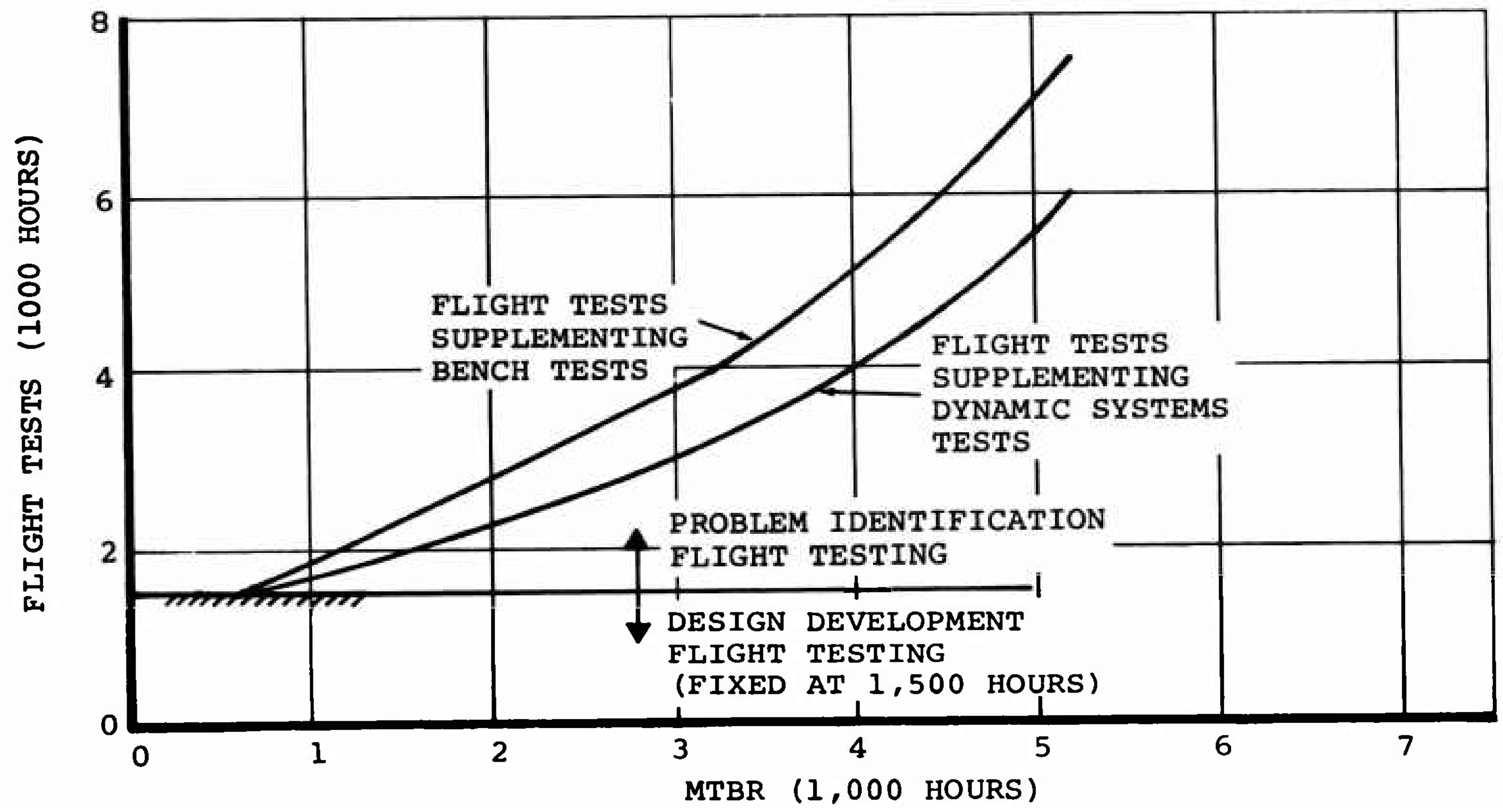


Figure 33. Flight Test Hours Required to Supplement Ground Tests for 3-Year Program.

3. Future efforts to reduce test costs by increasing the off-the-board MTBR must eliminate failure modes of rates heretofore considered acceptable by the designer. Design approaches which simply eliminate a few high frequency problems will not reduce test time (costs). Test durations are ultimately determined by the quantity of problems in the medium to low frequency range, since the high frequency problems are detected early in any test.

Elapsed Time

Three- , four- , and six-year elapsed time frames for testing were considered in structuring problem identification test programs. The minimum elapsed time considered was 3 years, since the necessary flight testing could only begin after 24 months (see Table XV). Intermediate lengths (e.g., 28 or 32 months) could be considered if appropriate for a specific development program.

Using the average cost lines from Figures 29, 30 and 31, the effect on time of three different required MTBR levels is shown on Figure 34. As expected, the programs for the lower required MTBR (600 hours) do not increase in costs with shorter program lengths, since the tests do not require the full amount of time available for completion. Consequently, the fixtures are not "doubled up" with shorter elapsed times. On the other hand, the more aggressive test programs (5200 hours) do have significant cost increases with shorter elapsed times, since test fixtures must be multiplied to accomplish the required test durations.

Component Development Programs

Current discussions of Military aircraft development programs frequently mention the "component development" phase. This phrase is usually intended to describe a preimplementation of design and test activity on those components or systems that are considered critical.

In the context of this study, a component development program which preimplements the design and testing of the major dynamic components would affect costs and schedules differently for various programs. For example, a 1-year preimplementation of a basic 5-year problem identification test program would not significantly reduce costs, but would allow completion of the development of the entire aircraft 1 year earlier in calendar time. On the other hand, the same preimplementation of a basic 3-year problem identification test program can reduce the costs (to a level approaching a 4-year program) but cannot reduce the elapsed time since the third year is still required for flight testing. As previously shown, the effects on costs and schedules due to preimplementation are also a function of the desired MTBR* level.

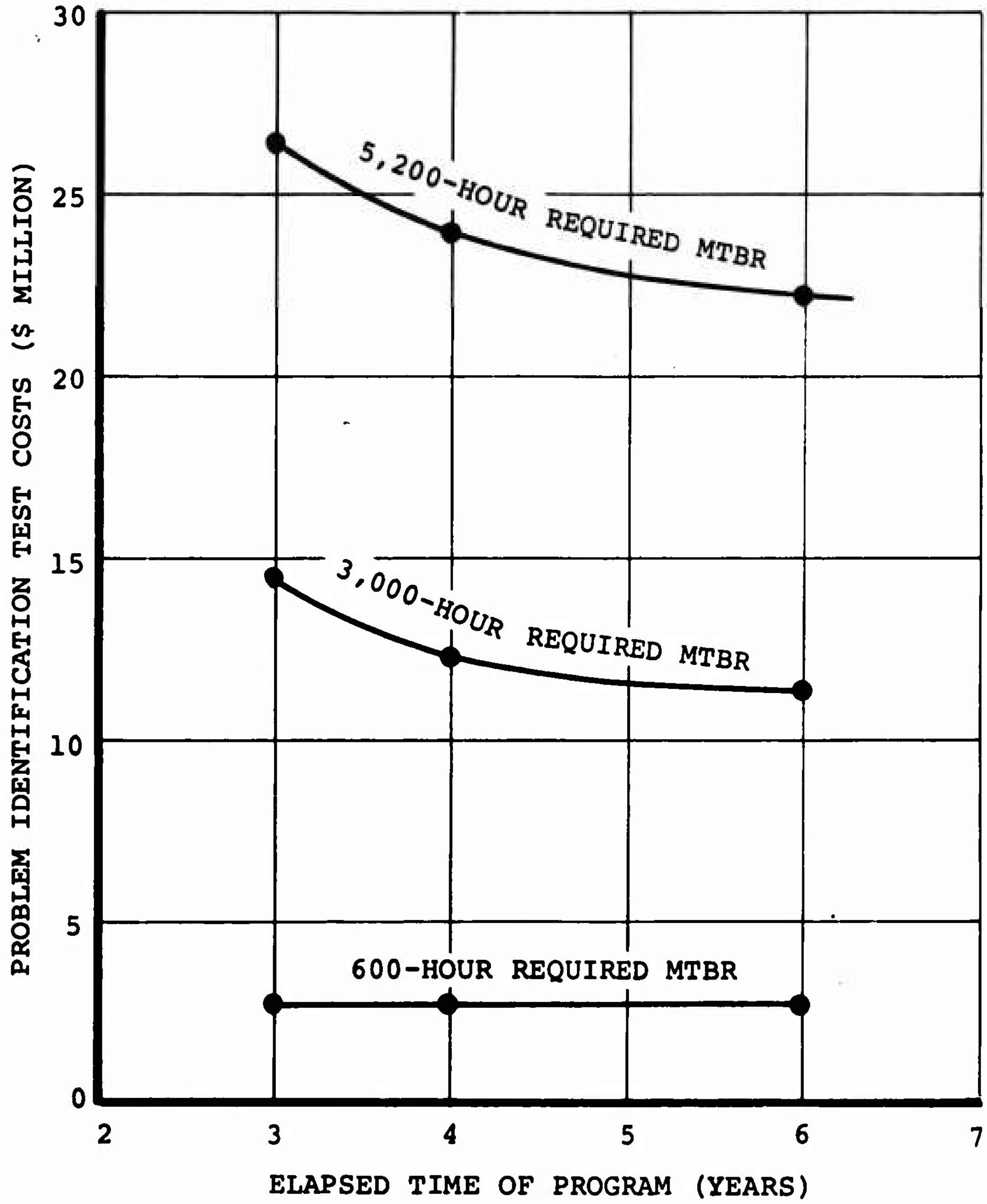
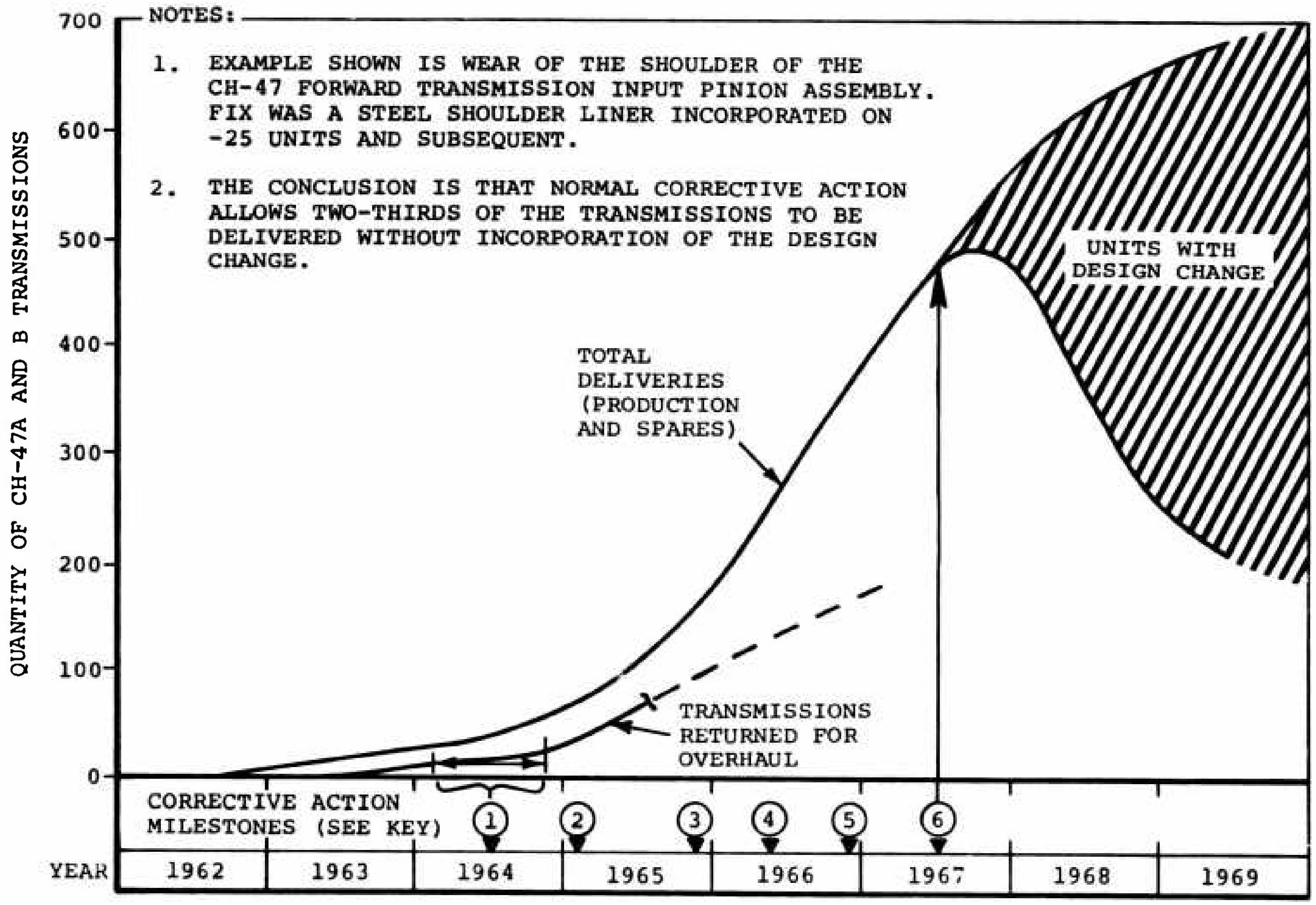


Figure 34. Effect of Program Elapsed Time on Problem Identification Test Costs.

In summary, any calculation of costs and schedule impact of a component development program must consider the basic MTBR* and confidence goals of the demonstration tests and the nature of the basic program to be preimplemented. However, the real value of a preimplementation or component development phase is not the effect upon development test costs, but rather upon total life cycle costs. Development tests take place within the larger framework of the production and delivery of aircraft and spares. On past programs, many of these deliveries have been unable to take advantage of the reliability improvements incorporated as a result of the test program. These components (having a lower MTBR) fail sooner and generate more aircraft maintenance and downtime, and consequently, more costs. The issue should not only be what MTBR is eventually produced from the test program, but also whether all of the components in the field possess the MTBR. A dramatic illustration of the importance of this viewpoint is shown in Figure 35; this actual CH-47 example suggests the potential cost savings of early corrective action implementation.

Proper evaluation of the cost impact of component development programs therefore requires a consideration of life cycle costs. This activity, beyond the scope of the study, could provide the data to quantify the value of preimplementation efforts.



CORRECTIVE ACTION MILESTONE KEY

1. WEAR OBSERVED ON 7 OF 30 UNITS
2. PROBLEM DEFINED
3. CHANGE DEVELOPED
4. ECP SUBMITTED
5. ECP COMMITTED TO PRODUCTION
6. HARDWARE AVAILABLE AND INCORPORATED ON AIRCRAFT

Figure 35. Typical Corrective Action Cycle and Unit Delivery Schedule.

6. DEMONSTRATION AND ITS INTEGRATION WITH PROBLEM IDENTIFICATION TEST PROGRAMS

The requirements of a formal demonstration test were explored in Section 2, where the various objectives of tests were defined. It was concluded that the nature of a formal reliability demonstration test which is an integral contractual element of the total program necessitates specific test criteria. As a minimum, these criteria should include flight loads and environments, a stable configuration, and adequate duration. Under these conditions, it is clear that the formal demonstration must be conducted on flight aircraft.

DEMONSTRATION POTENTIAL OF RELIABILITY PROBLEM IDENTIFICATION TESTING

Where contractual requirements to develop and demonstrate specific levels of product reliability are present, industrial management consistently asks the following questions:

1. How do we statistically interpret problem identification testing to assure that we are ready to enter the contractual demonstration?

2. Can we utilize successful problem identification testing as all or part of the contractual demonstration?

At the same time, the customer, for economic or other considerations, may have selected the concept of formal demonstration in the field with operational aircraft as his choice for formal demonstration, and hence may desire earlier reassurance that it is prudent to provide a production go-ahead from a product reliability standpoint. Here, the customer turns to problem identification testing as a source of assistance. The demonstration potential of problem identification testing must be evaluated.

Examination of past and anticipated future problem identification testing reveals a high probability that the test specimen configuration is not static, due to the constant need for incorporation and verification of corrective action. This, and the fact that problem identification test philosophy should be to "find problems" rather than "pass tests" (i.e., show that no problems exist), suggests that different statistical methods may be appropriate for problem identification testing than those applied to the formal demonstration.

Specifically, it may not be necessary for the problem identification testing to demonstrate that a finite MTBR level has been established at a finite confidence level, but rather only that satisfactory progress has been and is being made toward the final numerical goal. It must be recognized that in a successful problem identification test, the design (and

resulting MTBR) is constantly changing as corrective action is incorporated. In reality, even after the test is complete, all corrective action has not been verified or even incorporated. Thus, a rigorous statistical treatment of problem identification test results is inappropriate.

A more reasonable approach would involve the use of prior predictions at the failure mode level. Test results would be reviewed continuously to isolate any adverse trends. These trends would not be the mere appearance of failure modes, but the emergence of a pattern of unpredicted failures that might indicate a weakness in the design approach, tolerance buildups, higher loadings, etc. This pattern would suggest a higher latent failure rate than predicted and would therefore require a greater test duration.

In summary, the keynote of this process of demonstration would be application of engineering judgment as contrasted to the objective statistical treatment of the formal demonstration. Both contractor and customer would participate jointly in the effort.

FORMAL CONTRACTUAL DEMONSTRATION

In order to assure proper loads, environments and interfaces, it appears mandatory that demonstration testing consist of aircraft flight tests. Hence, demonstration costs become a function of only two variables:

1. The scope of effort paid for with developmental funds

2. Flight test demonstration duration

Two alternate approaches to demonstration have been suggested: (1) "demo-in", where the demonstration takes place early in the development cycle and is supported entirely from development funds, and (2) "demo-out", where the test takes place on operational aircraft in the field and development funds are required only for data collection and analysis.

The studies have been performed at nine demonstration values (500, 1,000, and 1,500 hours MTBR* at 30, 60, and 90 percent confidence) for both of the demonstration approaches. As used in the analysis, the only difference in these two approaches is the cost/hour values as shown on Table XV. The analysis considers demo-out programs of 3, 4, and 6 years, and demo-in programs of 4, 5, and 7 years. In the demo-in programs, 1 year is devoted to demonstration; therefore, the problem identification portions of both programs are the same (3-year demo-out has same problem identification tests as 4-year demo-in, etc.).

The extent of the demonstation test involves both elapsed time and duration considerations. The basic factor that must size the elapsed time is the amount of time that must be accumulated on any one component. At an aircraft utilization of 50 hours per month (Table XV), the maximum time on any one component would be 600 hours in 1 year. This is considered the minimum in which to determine if time dependent failure modes are present. In a demo-out condition, there will most likely be sufficient spread of time on parts to allow this 600 hours to occur over many ranges of component time. This is an advantage over the demo-in approach where all components, at that early stage of the program, would have relatively low times. Thus, with 1 year elapsed time established for demonstration, the duration (or number of aircraft) must be determined.

DETERMINATION OF OPTIMUM COST DEMONSTRATION DURATIONS

In Section 4 it was concluded that the effect of demonstration duration on the required MTBR was significant enough to require that the relationship be pursued in this study. Total reliability development test costs can be minimized by a process of simultaneously varying the demonstration duration in conjunction with the problem identification test program. Following is the trade-off study procedure:

1. For a given set of demonstration requirements (MTBR* and confidence), refer to the prescribed required MTBR vs demonstration duration plots on Figures 8, 9, or 10. For example, if 1,000-hour MTBR at 60 percent confidence is desired, the 1,000-hour curve on Figure 9 is appropriate.

2. Select the elapsed time of the problem identification test program. Refer to the proper problem identification costs vs required MTBR plot from Figures 29, 30, or 31. For instance, 3-year problem identification program costs are displayed on Figure 29.

3. Using the required MTBR as the common variable, plot the problem identification costs as they vary with demonstration duration. A 1,000-hour MTBR* at 60 percent confidence plot is shown on Figure 120 or 144 of Appendix V. (Appendix V presents individual trades for the 18 optimum points.)

4. Select either a demo-in or demo-out philosophy and construct a demonstration costs vs demonstration duration curve using the appropriate cost values from Table XV.

5. Add problem identification and demonstration cost values and determine the minimum cost point.

In order to maximize the usefulness of the trades, the problem identification test costs were an average of the bench and dynamic systems test programs. The curves on Figures 29, 30, and 31 labelled Average were used.

COST VARIATIONS WITH LEVEL OF DEMONSTRATED RELIABILITY

Table XVII summarizes the series of cost optimizations described individually in Appendix V. The table lists costs, the required MTBR, and the demonstration duration at the optimum point. The table also references the appropriate figures in Appendix V that show the complete cost optimization curves.

The cost impact (effect) of increasing MTBR* requirement can be summarized from this data, as shown in the example on Figure 36. This figure shows the costs for a 3-year demo-out program. In contrast, Figure 37 represents the cost of a 4-year demo-in program. The higher cost of demo-in programs becomes evident. The same data also illustrates the cost effects of increasing confidence levels (Figure 38). A third display is an "equal cost" plot where combinations of MTBR* and confidence can be selected for a fixed cost value (Figure 39).

These total test costs (problem identification plus demonstration) illustrate how demo-out programs are less sensitive to increasing MTBR* and confidence levels than demo-in programs. This "damping" is largely due to the technique of varying the demonstration duration. Utilization of this variable can be seen on Figure 40 (for increasing MTBR*) and Figure 41 (for increasing confidence). Displayed in both forms, the demo-out programs take greater advantage of longer demonstration durations because of the relatively low development-funded recurring costs of the demonstration test as opposed to the higher recurring costs of demo-in programs. The conclusion reached is that the technique of varying demonstration duration greatly minimizes the cost increases to achieve higher levels of demonstration MTBR* and confidence levels, especially for demo-out programs.

This procedure is not an academic artifice, but a realistic approach to reducing total program costs. The demonstration durations that result from the analysis are reasonable. The 22,000-hour duration (1,500-hour MTBR*, 90-percent confidence, and 3-year demo-out program) could be achieved with two companies of aircraft flying for 1 year at normal utilization. For demo-in programs, the 9,000-hour demonstration duration of the 4-year elapsed time 1,500-hour MTBR*, 90-percent confidence program could be achieved using only 12 aircraft for 1 year.

TABLE XVII. OPTIMUM COST POINT SUMMARY DATA FROM DEMONSTRATION AND PROBLEM IDENTIFICATION TEST COSTS TRADE-OFF STUDIES

Summary Data / MTBR* / Confidence	500-Hour 30%	500-Hour 60%	500-Hour 90%	1000-Hour 30%	1000-Hour 60%	1000-Hour 90%	1500-Hour 30%	1500-Hour 60%	1500-Hour 90%
3-Year Demo-Out (Fig. No.)	(116)	(117)	(118)	(119)	(120)	(121)	(122)	(123)	(124)
Required MTBR (hours)	590	740	796	1240	1610	2095	1810	2400	2980
Demo Length (hours)	1500	4200	10,200	2000	6500	15,000	4000	11,000	22,000
Optimum Costs ($ million)	2.9	4.4	6.0	6.5	9.0	12.9	9.4	13.4	18.3
4-Year Demo-Out (Fig. No.)	(125)	(126)	(127)	(128)	(129)	(130)	(131)	(132)	(133)
Required MTBR (hours)	590	720	790	1245	1640	2220	1910	2320	2830
Demo Length (hours)	1500	4600	10,600	1800	6000	12,000	2400	12,500	25,000
Optimum Costs ($ million)	2.4	4.0	5.5	5.4	7.4	10.8	7.7	11.3	16.0
6-Year Demo-Out (Fig. No.)	(125)	(126)	(134)	(128)	(135)	(136)	(137)	(138)	(139)
Required MTBR (hours)	590	720	800	1245	1590	2280	1830	2340	2880
Demo Length (hours)	1500	4600	10,000	1800	7000	11,000	3600	12,000	24,000
Optimum Costs ($ million)	2.4	4.0	5.4	5.4	7.4	10.7	7.7	11.1	15.8
4-Year Demo-In (Fig. No.)	(140)	(141)	(142)	(143)	(144)	(145)	(146)	(147)	(148)
Required MTBR (hours)	700	1200	1500	1460	2330	3280	2190	3660	4750
Demo Length (hours)	400	1300	2900	500	2500	5500	800	3400	9000
Optimum Costs ($ million)	4.2	9.1	14.7	8.3	17.2	29.5	12.5	26.3	46.3
5-Year Demo-In (Fig. No.)	(149)	(150)	(151)	(152)	(153)	(154)	(155)	(156)	(157)
Required MTBR (hours)	700	1380	1890	1440	2640	3430	2300	3600	4600
Demo Length (hours)	400	900	2400	600	2200	5200	600	3500	9400
Optimum Costs ($ million)	3.4	7.6	13.2	6.9	14.7	26.8	10.3	23.4	43.3
7-Year Demo-In (Fig. No.)	(149)	(150)	(158)	(152)	(159)	(160)	(161)	(162)	(163)
Required MTBR (hours)	700	1380	2050	1440	2490	3430	2350	3660	5400
Demo Length (hours)	400	900	2200	600	2200	5200	535	3400	7600
Optimum Costs ($ million)	3.4	7.6	13.0	6.9	14.5	26.3	10.1	22.8	42.1

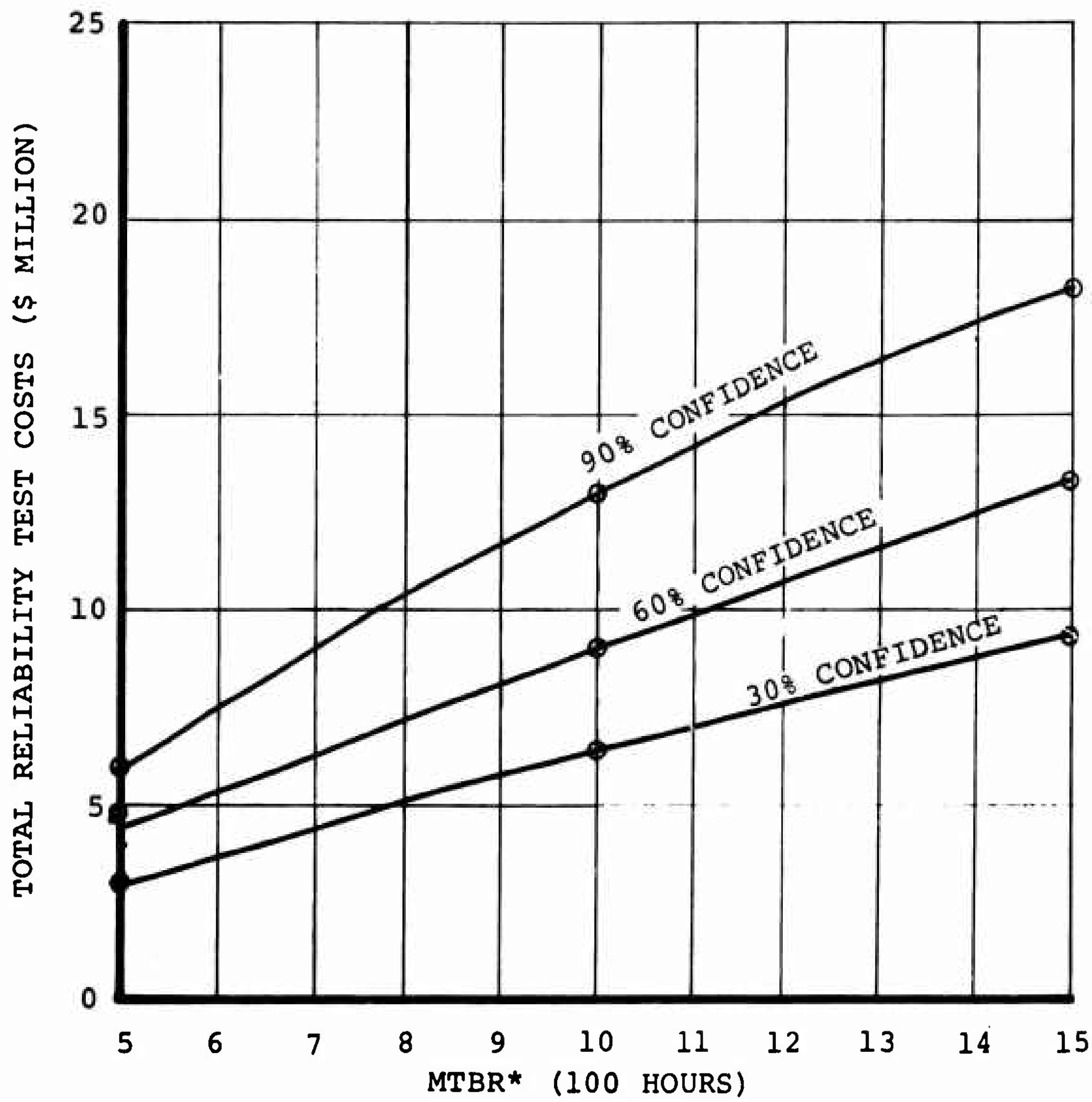


Figure 36. Variation of Total Reliability Test Costs With MTBR* for 3-Year Demo-Out Program.

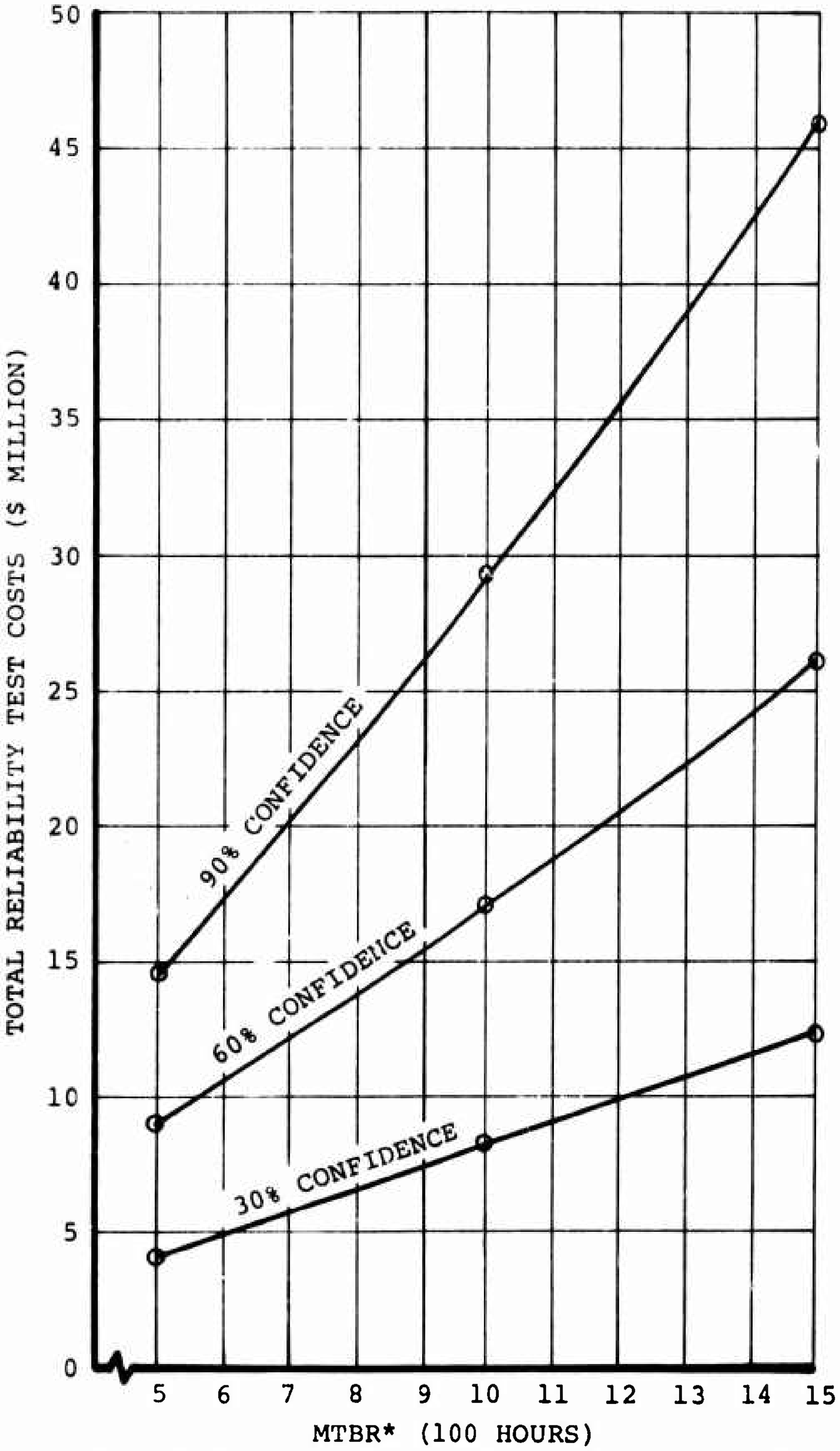


Figure 37. Variation of Total Reliability Test Costs With MTBR* for 4-Year Demo-In Program.

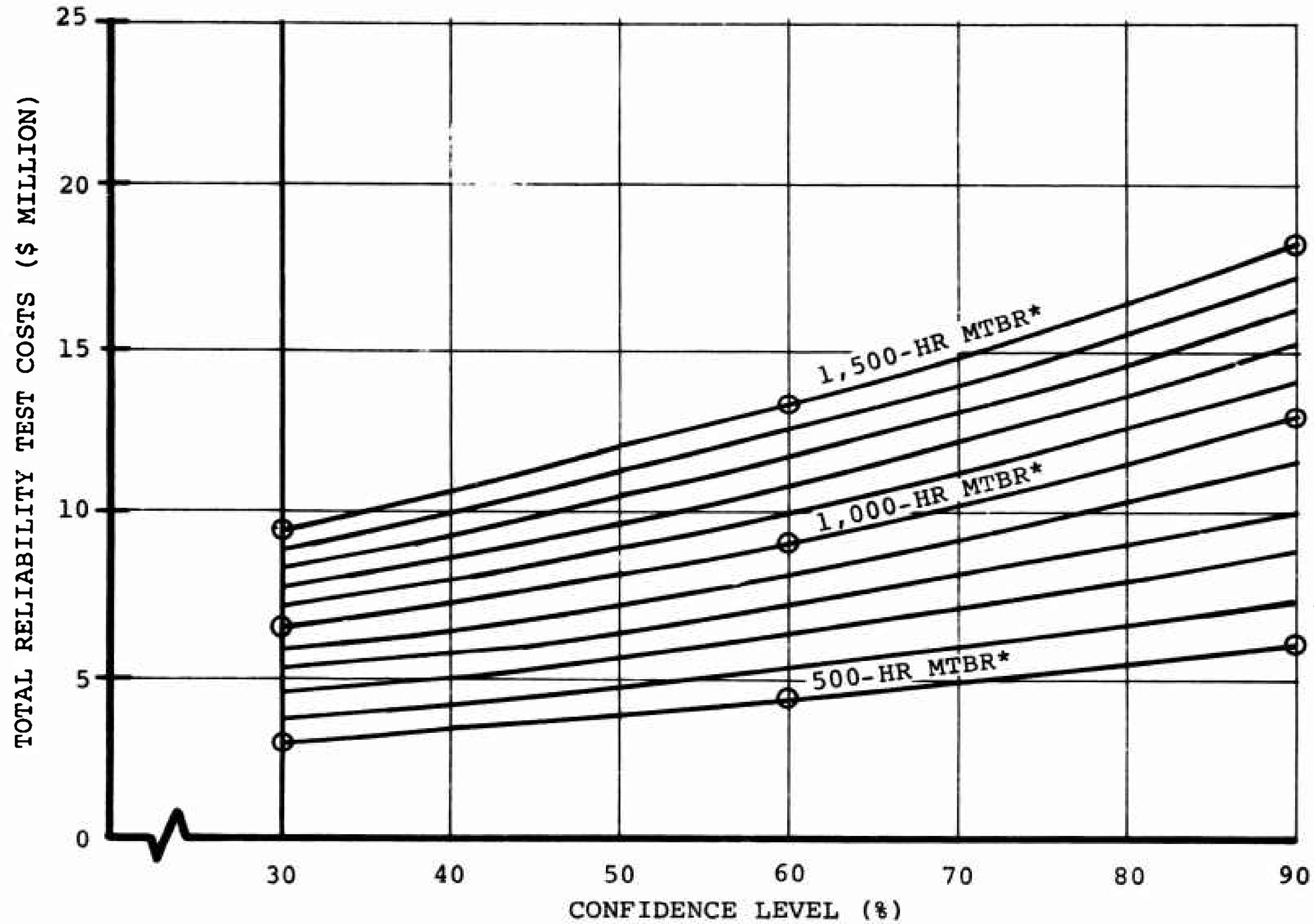


Figure 38. Variations in Total Reliability Test Costs With Confidence Level for 3-Year Demo-Out Program.

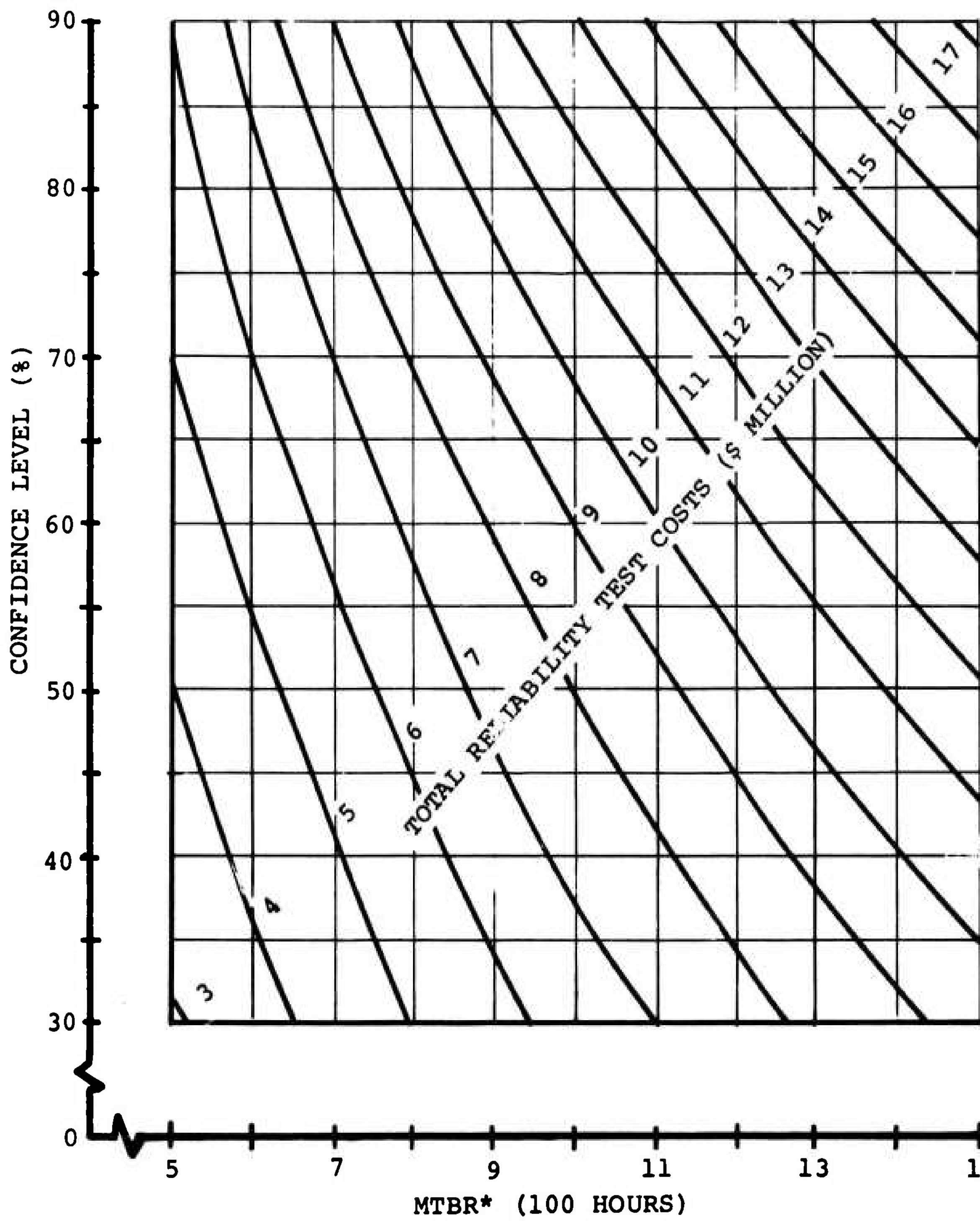


Figure 39. Combinations of MTBR* and Confidence Level for Equal Total Reliability Test Costs (3-Year Demo-Out Program).

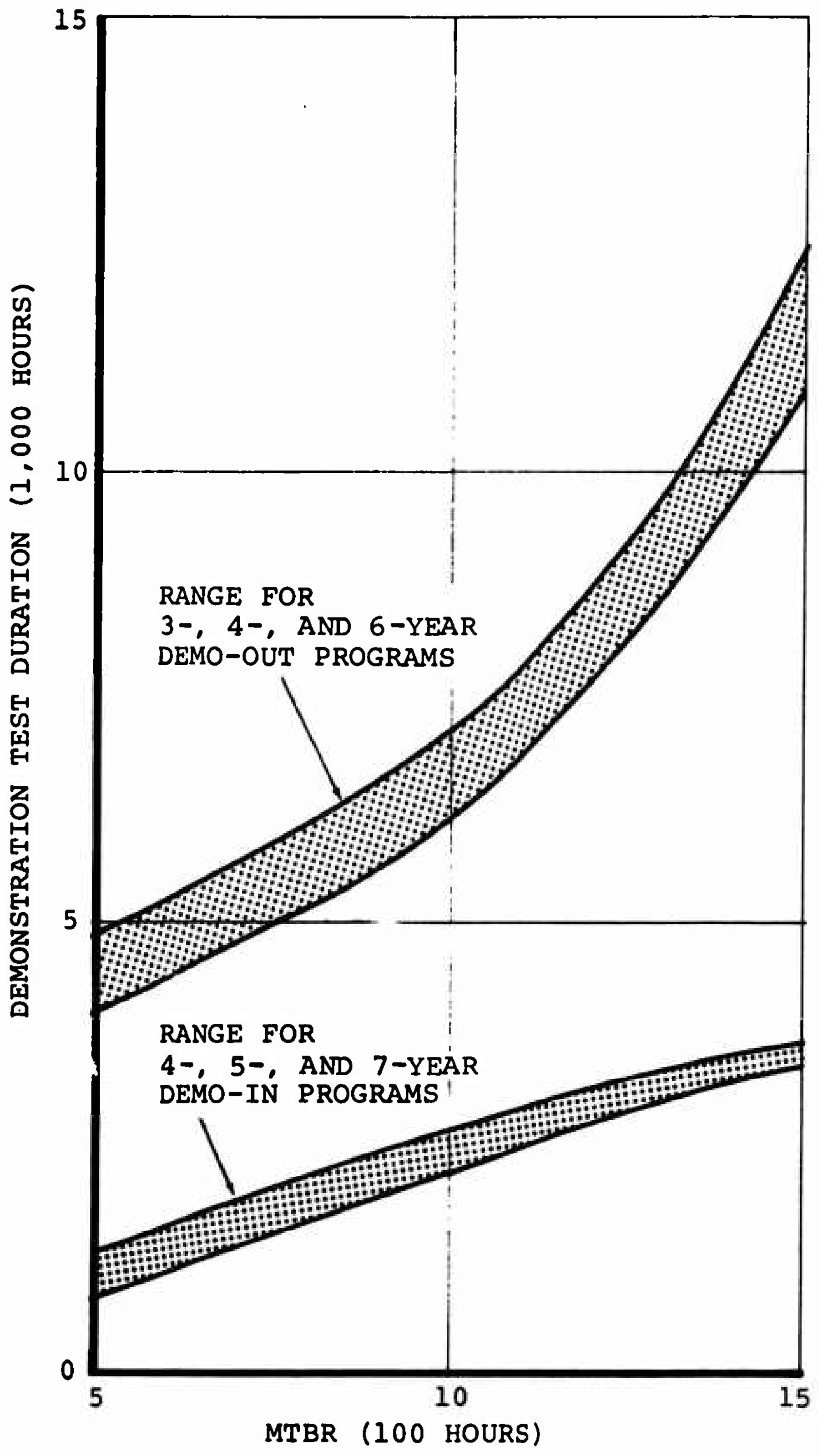


Figure 40. Effect of MTBR* on Optimum Demonstration Duration (at 60% Confidence Level).

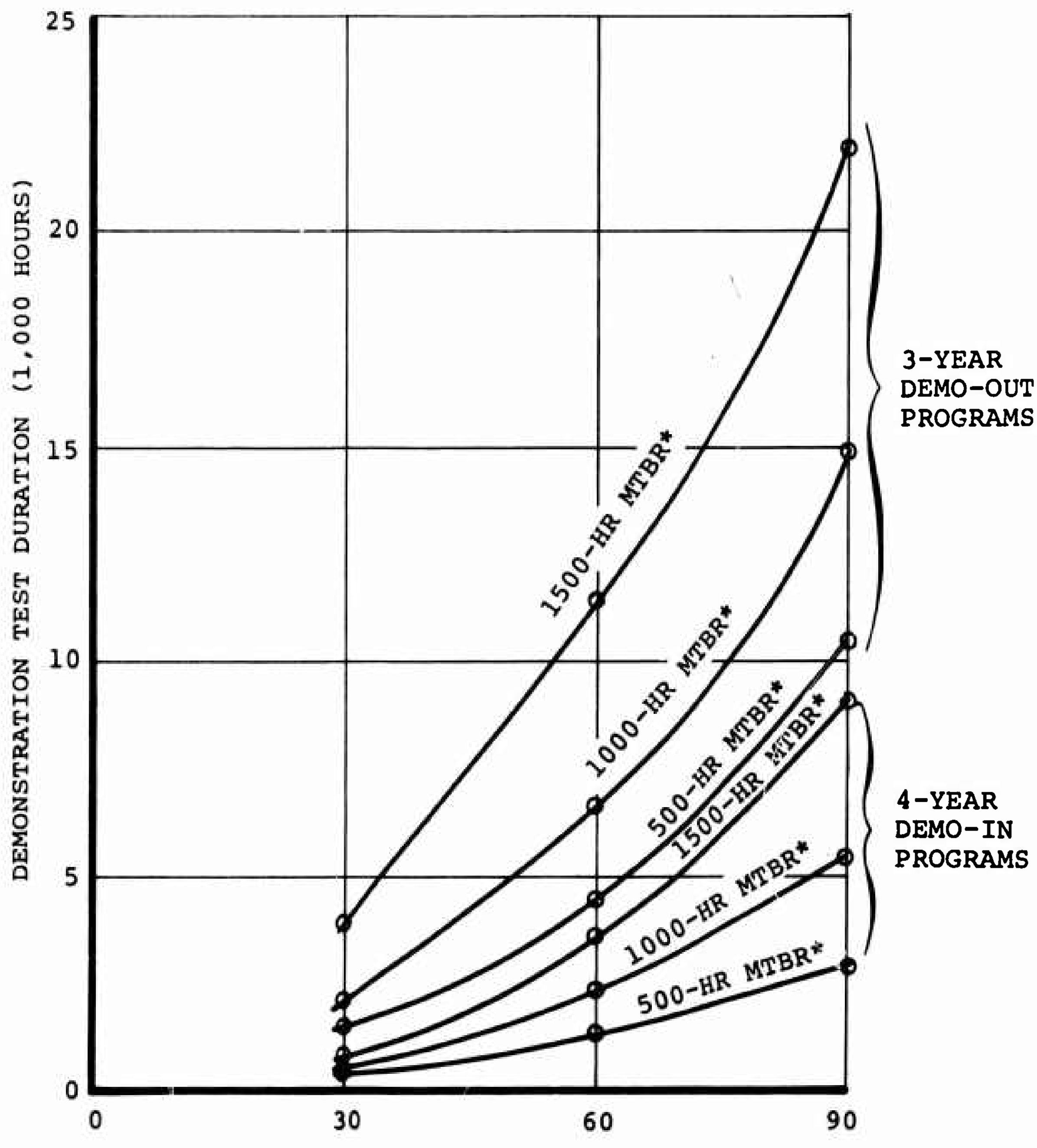


Figure 41. Effect of Confidence Level on Optimum Demonstration Duration.

THE VALUE OF DEMONSTRATION

The inclusion of testing for demonstration purposes in a total development test program imposes a penalty in terms of a reduced required MTBR being achieved.

If expenditures must be diverted to demonstration tests and away from problem identification tests, then the required MTBR produced will be lower than if all funds were concentrated in problem identification tests.

This required MTBR is not only a means of passing the demonstration test (as in the context of this study) but is also the actual reliability of the component. Although this cannot be demonstrated with a (relatively) short duration demonstration, the total population of components will eventually measure out to this value (assuming no further corrective action) during operational usage. This required MTBR ultimately defines life cycle O&M costs, and should therefore be of greater interest than the demonstrated MTBR*.

Recognizing this fact, the cost data from Table XVII has been plotted on Figures 42 and 43 against required MTBR: Figure 42 for demo-out programs and Figure 43 for demo-in programs. These particularly useful plots, while complex, show the relationship between demonstrated MTBR's* and confidences, problem identification and demonstration test costs (separately) and the required MTBR's.

In addition to the data from Table XVII, the problem identification test costs are also plotted against the required MTBR. This line, repeated on the demo-in and demo-out figures, is the same as the Average line from Figure 29. Thus, the distance (costs) between this line and any point above it represents the costs of the demonstration portion of that program.

Although costs were generated only for test programs demonstrating MTBR's* of 500, 1,000, and 1,500 hours at confidence levels of 30, 60, and 90 percent, interpolation between these points can be performed for intermediate values of MTBR* or confidence. To aid in this process, lines have been drawn connecting equal MTBR* or confidence values, with the intersections being the actual programs costed.

The plots serve many purposes. They illustrate the significant cost differences between the demo-in and demo-out programs. An obvious trend is how higher confidence levels raise the required MTBR above the demonstrated MTBR* at an ever-increasing rate. Perhaps the most interesting use of the plots is to examine what is obtained from a constant cost value. For instance, for $15 million with a demo-in program, 500-hour MTBR* can be demonstrated at 90 percent confidence,

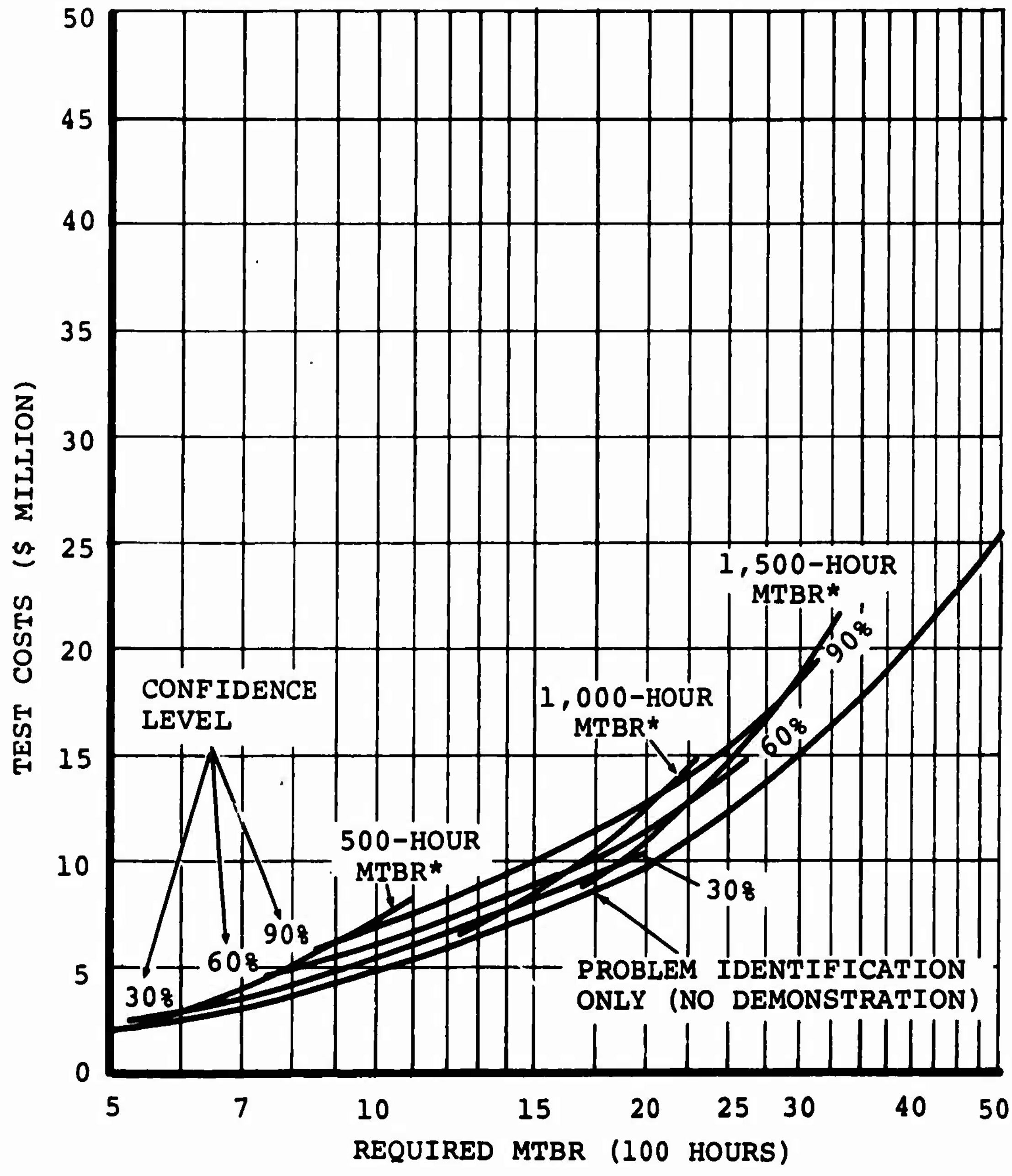


Figure 42. Relationship of Costs, MTBR, and Levels of Confidence for 3-Year Demo-Out Progr~ms (with 3-Year Problem Identification Tests).

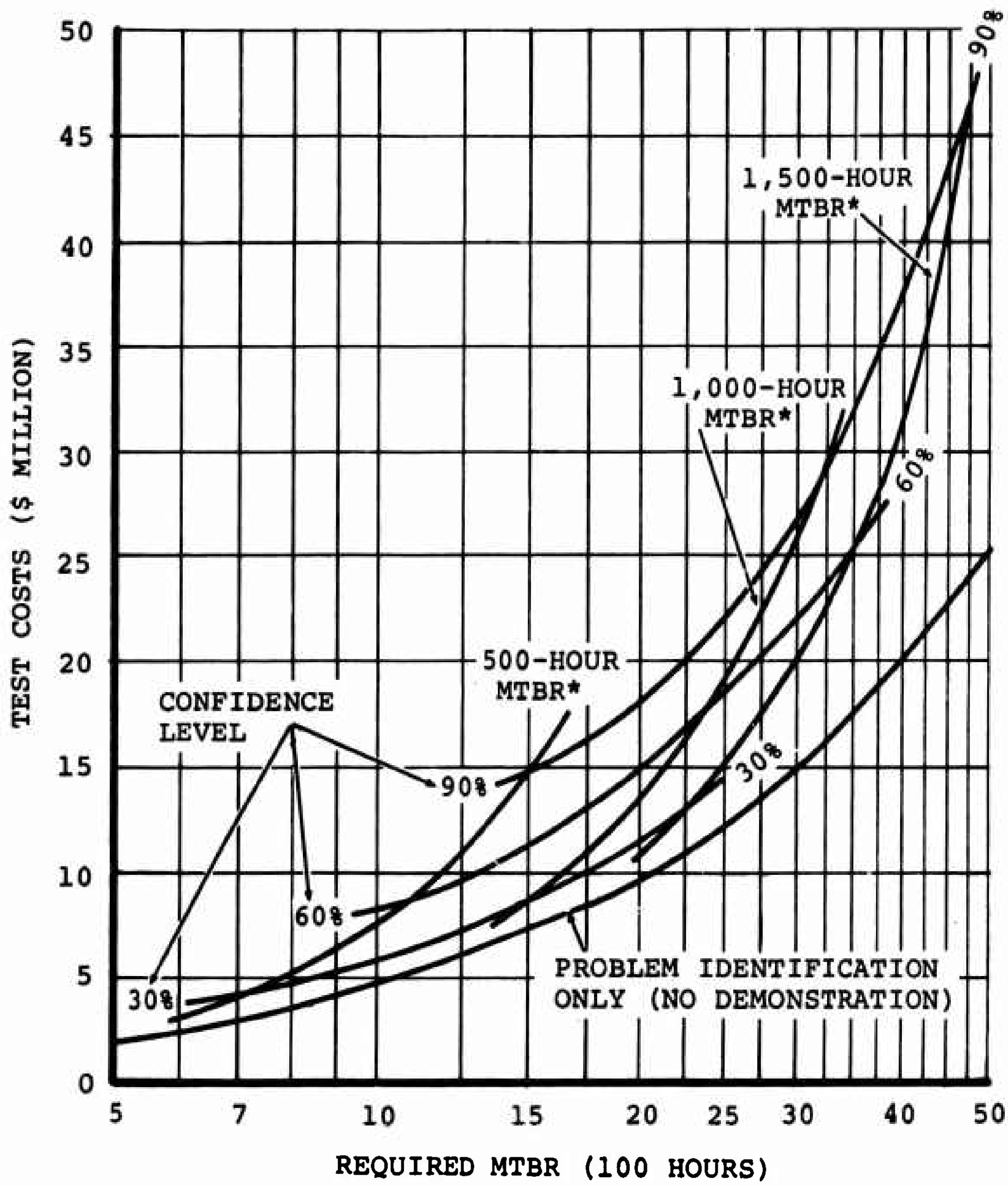


Figure 43. Relationship of Costs, MTBR, and Levels of Confidence for 4-Year Demo-In Programs (with 3-Year Problem Identification Tests).

achieving an actual required MTBR of 1,500 hours. Or, this same $15 million can be used to demonstrate 1,500-hour MTBR* at 40 percent confidence and achieve a 2,500-hour actual required MTBR. Or, with no demonstration, $15 million spent only on problem identification testing achieves an actual required MTBR of 3,000 hours.

The benefits of demonstration programs are more difficult to quantify than their disadvantages. Objectively stated, demonstrations attempt to improve contractor performance through the threat of some penalty, usually economic, and are therefore a management tool. The productivity of such an approach is, by nature, a matter of judgment. In determining the effectiveness of test programs throughout this study, it was always assumed that what could reasonably be done, would be done. The cost vs MTBR relationships depicted require highly motivated management and an aggressive, efficient execution of the test program. Demonstration tests, with incentives and penalties, can provide an atmosphere which encourages these attributes.

Given the premise that demonstration is desirable, the choice of demo-in or demo-out must still be resolved. The demo-in approach has a severe cost penalty but provides a numerical evaluation of the design at a point prior to a production commitment, where any necessary redesign has a minimum penalty on life cycle costs. The demo-out approach serves as a management tool and costs a great deal less than the demo-in program. However, the actual demonstration test occurs on production aircraft in the field at a time when many production aircraft and spare parts have already been delivered. Failure to meet demonstration requirements, would, in this case, cause heavy retrofit costs.

Further rigorous analysis of the value of these two alternatives (demo-in or demo-out) is not possible without considering life cycle costs in the framework of a specific aircraft development program, including both the financial and management areas of the program.

Consequently, it is recommended that additional research be directed at these two areas. First, the full life cycle costs impact of various MTBR's must be determined. This would have to be done for a variety of dynamic components, considering specific program aspects (e.g., delivery schedules). This would allow determination of the realistic cost increase for the reduced MTBR level that is achieved in a program that has alternate demonstration approaches. Secondly, an in-depth analysis of the financial aspects of a demonstration program should be made. This analysis would include consideration of possible contract penalty clauses, analysis of the manner in which the acceptable probability of passing the demonstration is determined, and an evaluation of the

degree of management response to a contractual demonstration environment.

This concludes the determination of the cost impact of demonstrating various MTBR* levels at various confidence levels. Other test costs are not affected directly by reliability requirements and will be examined in the subsequent section.

7. TOTAL TEST PROGRAM COSTS

Three types of tests were defined as being supported by developmental funds:

Type I General Design Development (Analytical Methods Confirmation)

Type II Reliability Problem Identification

Type IV Reliability Demonstration

The nature and costs of Type IV tests were explored in previous sections. Cost and effectiveness of Type II tests were analyzed for variations caused by increasing reliability requirements. However, not all costs associated with Type II tests have been addressed: specifically, tests performed on the entire aircraft under extreme environmental conditions (e.g., those performed at Yuma, Eglin, or Alaska), and costs to implement corrective action required from problem identification during the Type II test program.

These cost elements and the rationale and derivation of the Type I test costs are discussed in this section.

TYPE II CLIMATIC ENVIRONMENTAL TESTING COSTS

Evaluation of environmental tests, in terms of the major dynamic components, is hampered by the fact that they are traditionally performed on the completed aircraft. For example, during the cold-temperature tests, major emphasis is placed on such subsystems as hydraulic, pneumatic, and electrical. Engines and rotor subsystems are of particular concern during desert tests. It is difficult to properly evaluate the overall cost-effectiveness of such tests considering only the main dynamic components. Further, these tests are conducted to reveal problems at climatic extremes and are usually without concern for the MTBR level desired; hence, their duration and costs are not readily relatable to numerical reliability requirements.

The primary concern of environmental tests is with the failure modes induced by the particular environment. These problems can frequently be detected quickly, requiring minimum test duration. The following are examples of cold-temperature problems that occurred involving short test durations:

1. Rotor sleeve bearing displacement due to ice

2. Rotor blade box unbonding

3. Oil filters bypassing

Problems induced by desert operations are more sensitive to time (e.g., blade erosion); nevertheless, trends can generally be developed without significantly extending duration. Thus, the duration of each climatic environment test is fixed at 40 flight hours.

The costs of environmental tests have been added as fixed values to the variable Type II test costs previously established. CH-47 experience has been used as a base, with one exception: the duplicate testing performed at Eglin and Alaska has been eliminated because actual Alaskan flight testing is preferred to the Eglin tests (which, as a tiedown test, has reduced effectiveness). Cost elements for the CH-47 tests were provided by USAAMRDL and were extrapolated by Boeing to Helicopters "A" and "B".

COSTS OF CORRECTIVE ACTION RESULTING FROM TYPE II TESTING

In this study, the costs of testing for each test technique included engineering test monitoring, material costs to overhaul/reconfigure test specimens, and the necessary test duration to verify corrective action adequacy. The basic design activities of determining the cause of problems, subsequent redesign, and formal drawing release have not been included. These activities are primarily performed by design and support staffs which remain after initial design is complete. The staffing levels may not be directly relatable to the number of problems to be resolved. Historically, the budget for these groups is not usually derived from developmental testing funds. Nevertheless, these corrective action design costs are of interest in estimating the total cost of development programs.

Hence, design and support costs have been predicted for corrective action. The calculation of design support costs is based on the number of problems which must be eliminated to achieve the specific required MTBR, with (an assumed) 700 man-hours required per problem solution.

For Required MTBR of:	Helicopter "A" and "B" Design Support Costs are:
600 Hours	$1.1 Million
3,000 Hours	$1.3 Million
5,000 Hours	$1.4 Million

This relationship between required MTBR and costs reflects the failure frequency distribution of the failure modes. That

is, the majority of problems must be corrected to achieve even the relatively low MTBR of 600 hours with a rather small number requiring further correction to achieve significantly higher levels of MTBR. Of the test programs designed to meet the reliability requirements (500, 1,000 and 1,500 hour MTBR* at 30, 60 and 90 percent confidence), most have required MTBR's in the range of 1,000 to 2,500 hours. The design support costs in this range are approximately $1.2 million. Total reliability test costs for demo-out programs in this range are $8 to $13 million. Thus, the design support costs are an increment of from 9 to 15 percent added to basic Type II and IV tests costs, if this cost accounting is considered appropriate.

TYPE I TEST COSTS

The characteristics common to Type I tests have been discussed in Section 2. The factors affecting the amount of testing performed in this category were also outlined. A review of this is appropriate to understand the specific cost estimates made for Helicopters "A" and "B" on Table XV.

The most important common characteristic of the tests is the effect of their specialized objectives upon the conditions, configuration, and criteria of the tests. Type I tests have already been optimized to achieve their specific objectives in the shortest time and with minimum cost. Further reductions in total program costs could only be achieved by having Type I and II objectives jointly satisfied by single tests, or by having a sheer reduction in the objectives of Type I tests. Both approaches are considered here.

Four groups of objectives encompass most of the Type I test requirements:

1. Materials and dynamics evaluation

2. Single failure mode investigation

3. Strength determination

4. Aircraft performance assessment

Materials and Dynamic Evaluation

Evaluation of materials is normally performed via bench tests very early in the design phase, before configuration details have been established. Coupon ultimate and fatigue tests and grease and oil evaluations are examples of material evaluation tests. The evaluation of dynamic characteristics takes place on detailed components, completed assemblies, or the entire aircraft; thus, both ground and flight tests are used. They include gear resonance surveys, spring rate determinations, and strain and vibration surveys. The requirement for these

tests is accepted and not controversial.

Tests in this group are not susceptible to either reductions in scope or further integration of objectives with Type II tests. Material evaluation tests are uneconomical to perform with configured hardware to identify reliability problems. Also, they have scheduling requirements which would ultimately preclude this. Reductions in scope can only occur where relatively few materials/concepts are being considered for application in new aircraft.

Dynamic characteristics evaluations are nearly always extremely short-duration tests with highly instrumented hardware. They cannot economically be further integrated with long-duration Type II testing since the expensive instrumentation is not required for Type II objectives. Conversely, the state of the art in dynamic system analysis precludes significant reduction in contemporary levels of dynamic evaluation.

Single Failure Mode Investigations

Tests in this category are prompted by past safety and reliability experience on similar design concepts. Examples are tests designed to explore one aspect of a design concept such as clutch wear or blade erosion. Performance of these tests usually requires the application of unique loads, speeds or environments which dictate that specialized tests be created. Reductions in the scope of this effort may be feasible if not in conflict with safety considerations, the numerical reliability requirements, or the availability of alternate design concepts.

For both the single failure mode investigations and material and dynamic characteristic evaluation categories, the CH-47 nonflight costs were relatively insignificant (labeled "miscellaneous" on Table XV). For Helicopters "A" and "B," they were costed based on the anticipated degree of use of new materials or design concepts, and with appropriate new costs to assure that specific historical problems do not appear.

Strength Determination

The strength determination group of Type I tests consumed approximately 96 percent of the costs of Type I ground tests on the CH-47 (see Table XV).

Primary emphasis is directed at fatigue tests, as opposed to static load tests, since they contributed over 94 percent of the CH-47 costs in this group. Fatigue tests define the load vs life characteristics for components in the major dynamic systems. Complete understanding of these characteristics is necessary because fatigue failures in critical dynamic components, with a historical tendency to undetectability, have catastrophic implications. It is therefore required that fatigue tests be performed at the earliest possible time to preclude massive program delays due to redesign, unacceptably low TBO's or retirement lives in the field, or unsatisfactory flight safety. When performed with individual components on test fixtures which apply loads at relatively high frequency (30 cps), fatigue tests can be accomplished in extremely short elapsed time. Another factor which promotes specialized fatigue tests is the magnitude of the loads involved. Components designed for basically unlimited fatigue life (standard Boeing-Vertol policy on dynamic components) require applied loads greatly in excess of normal flight loads to produce the fatigue failures necessary to define the complete load-life relationship. Achievement of these loads is difficult on complete assemblies because the dynamic characteristics of the designs and the travel capability of test fixtures are usually incompatible, and there are limitations of some related components in withstanding handling the loads.

To illustrate the first reason, the required loads for the rotor pitch housing arm, when reacted in the normal fashion by the tension-torsion coupling, required displacements beyond the capability of available rotating-mass fatigue machines. To overcome this, the component was mounted rigidly to the test fixture without the usual bearings, seals or tension-torsion couplings. Thus, the full assembly was not tested.

To illustrate the second reason, fatigue test of the rotor swashplate pitch link clevis lugs required loads beyond the capacity of the main swashplate bearing. Therefore, the swashplate was mounted rigidly and separately for fatigue tests of the pitch link clevis.

For similar reasons, a whole family of specialized fatigue tests has been developed. It is a need that arises, paradoxically, from higher (or unlimited) fatigue lives, designed into the component. This condition is not universal; designs which have lower stress margins permit the acquisition of fatigue data during assembly testing at reasonably realistic load levels. Here, Type I and Type II test objectives may be integrated with substantial cost reductions. One such attempt at this integration is the installation of aerodynamic panels under rotor blades being tested on a whirl tower (Reference 4). This procedure offset the absence of forward flight airflow and produced flap bending loads at

109 percent of the maximum in-flight loads. This data was only of value, however, under conditions where the normal flight loads frequently exceeded the fatigue endurance limit (as they did in this instance). Where the endurance limits are substantially above all flight loads, attainment of loads high enough to fail the component can only be achieved with specialized tests.

Once committed to a specialized fatigue test, the next significant cost variable is the number of specimens required in the test. Since the number of test points is essentially the same for all reasonable S/N curves, numerical reliability requirements do not appear to significantly affect this variable. More important to this determination is an intricate combination of factors such as the statistical methodology to be used on the tests results, the materials and designs to be tested, and the level of confidence (or program risk) that is desired.

A desire to increase confidence or reduce program risks was manifested on the CH-47 by a continuation of fatigue tests after the first group of specimens. As can be seen in Appendix III, the first "phase" of fatigue tests was completed early in the program with two additional phases following. The additional phases utilized, on the average, 30 percent of the number of specimens in the first phase. Reliability requirements do, however, occasionally affect the detailed configuration of the fatigue test specimens and the method of application of loads. A review of CH-47 field problems (Appendix II) suggests that the relatively few fatigue problems not detected in tests could be attributed to either the absence of the specific component during the tests or the lack of (or misapplication of) loads. Examples of this are the blade damper quick-disconnect "D" handle shaft which was replaced by a bolted connection in the tests, and the lack of rainshield airloads upon the swashplate drive collar during tests.

It is beyond the scope of this study to completely explore the variety of detailed improvements that could be directed at Type I fatigue tests. Their presence, however, is acknowledged by increases in the costs for Helicopters "A" and "B" to reflect additional requirements in future programs.

In summary, the following assumptions were made to determine costs for the strength determinations group of Type I tests:

1. A fatigue design philosophy of infinite endurance limits.

2. The utilization of new materials and design concepts as proposed in the specific designs of Helicopters "A" and "B".

3. "Confidence" in the test results or program risk levels consistent with the projected contractual environments for Helicopters "A" and "B".

4. Incorporation of improved statistical treatment of test results.

5. Application of more complex loads on more completely configured specimens.

6. The number of specimens reflect only a "first phase" program.

Aircraft Performance Assessment

This is flight testing to establish aircraft load, stability, and performance characteristics. Costs of this far surpass the costs for the other groups of Type I testing.

The main variables here are the duration of the flight testing and the operating costs per hour. Derivation of appropriate Type I duration is difficult due to the intermixing of Type I, II and III objectives during past flight testing programs. Several past and projected program flight test durations illustrate this:

Aircraft	All Type I, II and III Flight Tests (Hours)	Type I Only (Hours)	
H-3	5,000	(?)	Reference 3
H-53	1,400	(?)	Reference 3
H-54	900	(?)	Reference 3
H-47	2,400	1,700	Appendix III
Model 187-2 (Boeing)	6,100	1,900	
Model 300-S2-106 (Boeing)	5,100	1,200	

Detailed information was not available on the Type I portion of the first three aircraft listed. The CH-47 test history (Appendix III) was reviewed in detail with the Type I objectives representing approximately 70 percent of the total. The Model 187-2 and 300-S2-106 values are estimates made for these aircraft by Boeing independent of the study effort, and reflect (in the case of the 300-S2-106) specific program considerations (component development program). Based on this history and the inevitable escalation of requirements, the Type I flight testing value has been fixed at 1,500 flight hours for both Helicopters "A" and "B". Type I operating costs are high on a per flight hour

basis (Table XV), due primarily to the rather low utilization of the aircraft and to instrumentation requirements. With such high expenditures, it is mandatory that all Type I flight testing be analyzed to identify reliability problems, thus contributing to the satisfaction of Type II objectives. The value of flight testing for problem identification is in its effectiveness (100 percent). Thus, the 1,500 hours of Type I testing is counted as problem identification testing, hour for hour, in each of the candidate test programs previously costed. However, the entire cost of this flight testing is counted against Type I only.

TOTAL DEVELOPMENTAL TEST COST SUMMARY

The elements comprising total developmental costs are the variable Type II test (problem identification) costs, Type IV (demonstration) test costs, fixed (relative to MTBR) Type II costs, and Type I test costs. An overview of these is in order.

Cost Sensitivity to Reliability Requirements

The total costs of several development test programs for Helicopter "A" have been graphically summarized on Figure 44. These programs represent contrasts in the variables that determine costs. The effect of increased demonstration MTBR* is evident when comparing bars number 1 and 2 (on Figure 44). The most significant variable, demonstration philosophy, is altered between bars number 2 and 3. Note that bars number 1 and 3 have the same required MTBR. Bar number 4, with the same demonstration philosophy, reduces only the confidence level. As an extreme, bar number 5 represents the lowest cost program (within the confines of this study).

From the comparisons, the effect of the major variables can be perceived.

Clearly, the two variables having the largest impact on costs are demonstration philosophy ("have" or "omit", and "in" or "out") and the demonstrated MTBR* and confidence levels. Other variables such as the mix of test techniques and the elapsed time of the program appear to be less significant. The selection of demonstration philosophy and the reliability demonstration levels are, in reality, related issues. Both are associated with the much larger matter of life cycle costs. Both decisions should be made with the sole objective of minimizing total program costs.

Test Costs Insensitive to Reliability Requirements

The cost data summarized on Figure 44 indicates that a large portion of total test cost is independent of numerical reliability requirements. This suggests that attention at least equivalent to that expended on reliability-driven costs should be focused on this area. Some of the more obvious variables affecting these Type I costs have been discussed. Additional research must be directed at evaluating the cost-effectiveness of Type I tests against their unique objectives.

Specific areas for further study follow.

Flight Testing

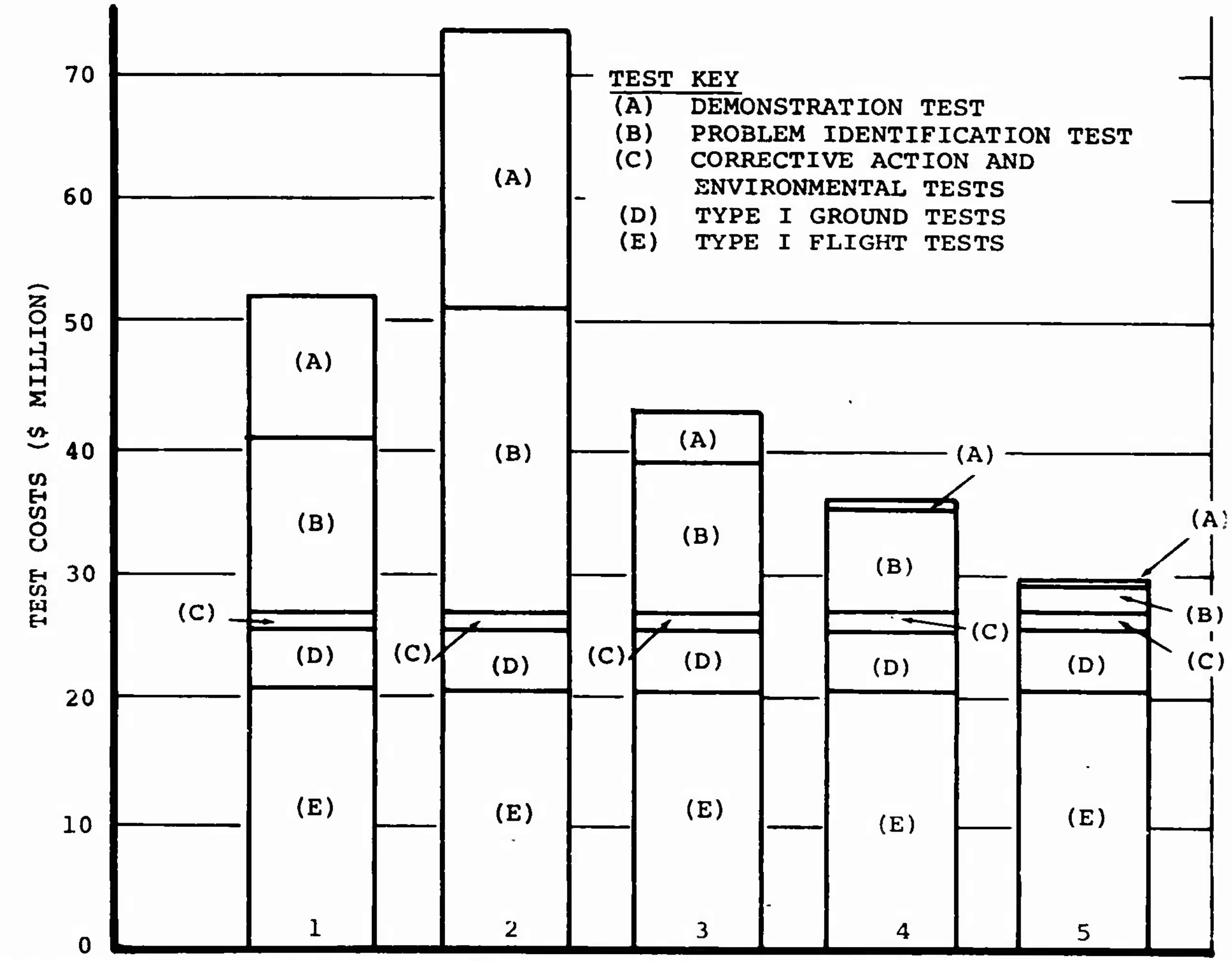
Of all the estimates in this study, derivation of the Type I flight testing costs is the most fragile, because the costs are sensitive to many unique program considerations and historical data of the required detail is difficult to obtain.

Information is required to describe the specific purpose of each test hour, provide accurate breakdowns of support costs, and identify the factors contributing to aircraft downtime. Flight test costs are extremely dependent upon utilization (flight hours per calendar time), yet it is traditional to treat costs per flight hour as a parameter that is insensitive to utilization. Estimation techniques that acknowledge utilization, combined with improved component reliability that increases utilization, might reduce predicted test costs in future programs.

Therefore, one potentially profitable area for future research is to thoroughly analyze the manpower expenditures and flight scheduling of past flight test programs. The effort would examine the required test duration to satisfy specific Type I objectives, isolate flight testing for Type II purposes, and identify/quantify factors resulting in low utilization or requirements for retesting. Engineering, manufacturing, instrumentation, and other costs would be examined in detail. With this foundation, the specific objectives of Type I flight testing could be reviewed, with cost reduction as the ultimate goal.

Ground Testing

Type I ground testing is largely composed of fatigue tests. Cost reduction can only occur if the variety of tests or number of test specimens is reduced. Fixture and operating costs appear to be relatively fixed. No reduction in the number of individual types of fatigue tests is contemplated.



DEMONSTRATION APPROACH	DEMO-IN	DEMO-IN	DEMO-OUT	DEMO-OUT	DEMO-OUT
MTBR* (HOURS)/CONFIDENCE (%)	1000/90	1500/90	1500/90	1500/30	500/30
ELAPSED TIME (YEARS)	4	4	4	4	6
REQUIRED MTBR ACHIEVED (HOURS)	3000	4750	3000	1900	590
DEMONSTRATION DURATION (HOURS)	5500	9000	25,000	2400	1500

Figure 44. Summary of Total Development Test Costs.

A great deal of research into fatigue testing has been performed, largely by the stress and mathematical communities. Two areas have received concentrated attention. One area addresses the detailed improvements that are required in the analytical predictions of load paths and the methods of test load application. The second area is the progress and application of improved statistical treatment of test results. An example of the latter is Reference 5. Both of these areas usually explore how existing levels of effort can be refined to improve their usefulness. Few studies, if any, approach the problem from the viewpoint of how, with given requirements, the fatigue test can be reduced in number of specimens, or, preferably, total costs. Future research should be directed at quantifying the objectives of fatigue tests and the effect of these objectives upon test costs. With this relationship, program managers can make more intelligent decisions concerning the distribution of development test costs.

Another area of potential savings is in (sequential) specimen utilization. Specifically, it might be feasible that specimens from the Type II tests be subsequently used for Type I tests. If some, or all, of the fatigue tests were scheduled for performance after Type II tests, significant savings could be realized. Before this could occur, we should examine the analytical methods available for considering past loads applied to the specimen during Type II testing, and the probability that redesign caused by Type I test results would invalidate the Type II tests.

8. SAMPLE TEST PLAN

Complete development test plans have been constructed for both Helicopters "A" and "B" to illustrate the impact of variations in helicopter size, weight, and configuration. These programs are designed to demonstrate an MTBR* of 500 hours at a confidence level of 60 percent in accordance with study contract requirements. The problem identification portion of the program is a 3-year period, and the demonstration is a demo-out type.

Both programs include Type I ground and flight testing, and Type II and IV testing are integrated to produce the lowest costs. The complete schedules are shown on Figure 45 for Helicopter "A" and Figure 46 for Helicopter "B". Descriptions of test setups are provided in Appendix VI.

HELICOPTER "A"

The Type I costs have previously been shown on Table XV and are summarized as follows:

Type I Tests	Average Number of Specimens	Cost ($ million)
Fatigue, Rotor Components	9	3.06
Fatigue, Control Components	8 (Includes 2 hogouts)	.67
Fatigue, Drive Components	10	1.10
Static Load	2	.31
Miscellaneous	-	.31
	Subtotal	5.45
Flight (1500 flight hours at $13,500 per hour)		20.32
	Total	25.77

For the required MTBR and elapsed time, the Type II tests are most economically performed with a bench-type program. The costs to achieve various required MTBR's are therefore represented by the "A" curve of Figure 29. These costs, when integrated with demonstration test costs (Figure 47), produce a minimum cost point of $3.7 million at a demonstration duration of 4,600 hours and a required MTBR of 720 hours.

Of this $3.7 million, the demonstration costs are $.92 million and the Type II tests costs are $2.78 million. An additional increment of nonvariable Type II test costs (for environmental tests) is added to produce:

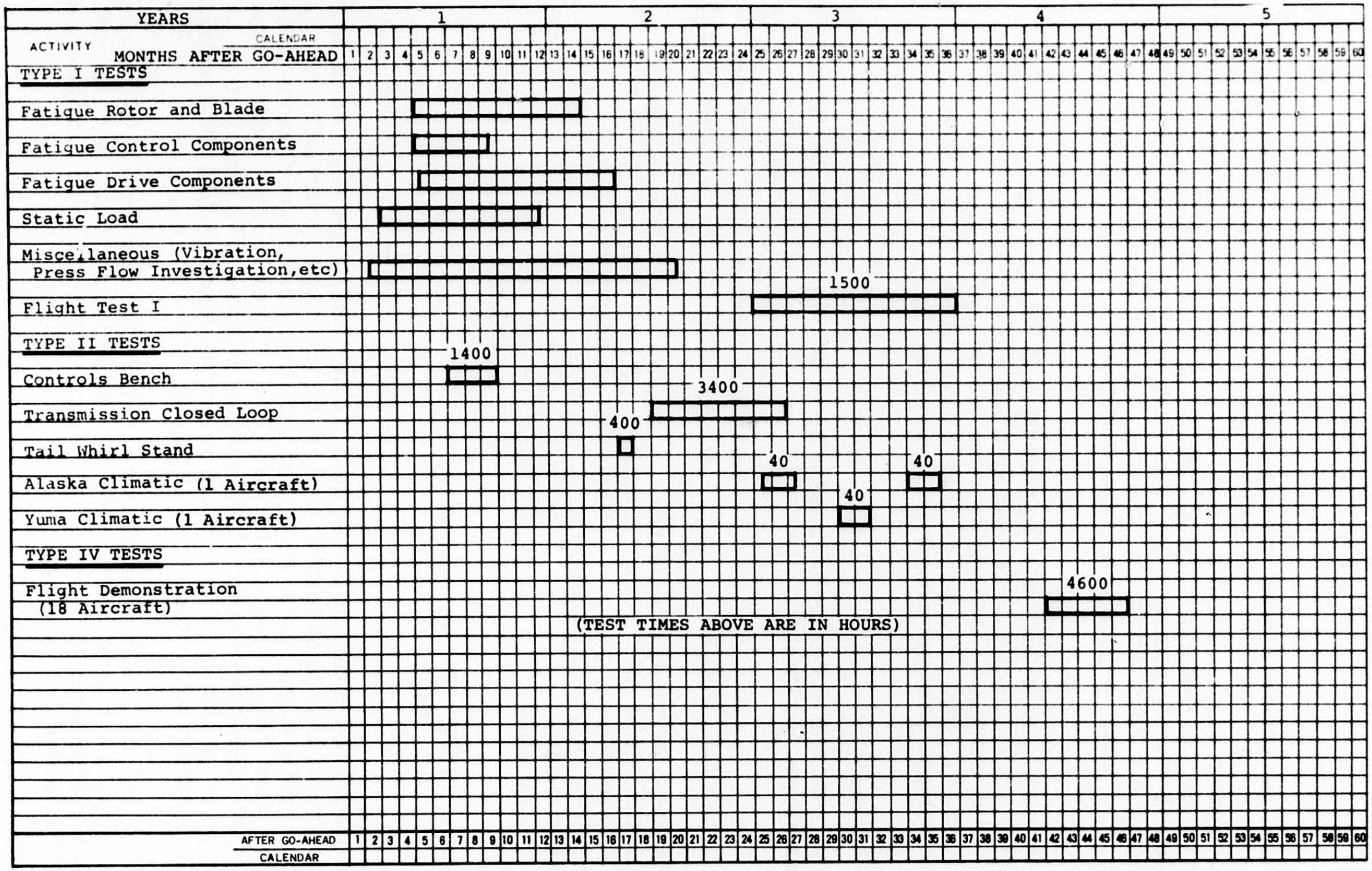


Figure 45. Helicopter "A" Test Plan Demonstrating 500-Hour MTBR*, 60% Confidence, 80% Probability of Passing Demonstration, and 3-Year Problem Identification Demo-Out.

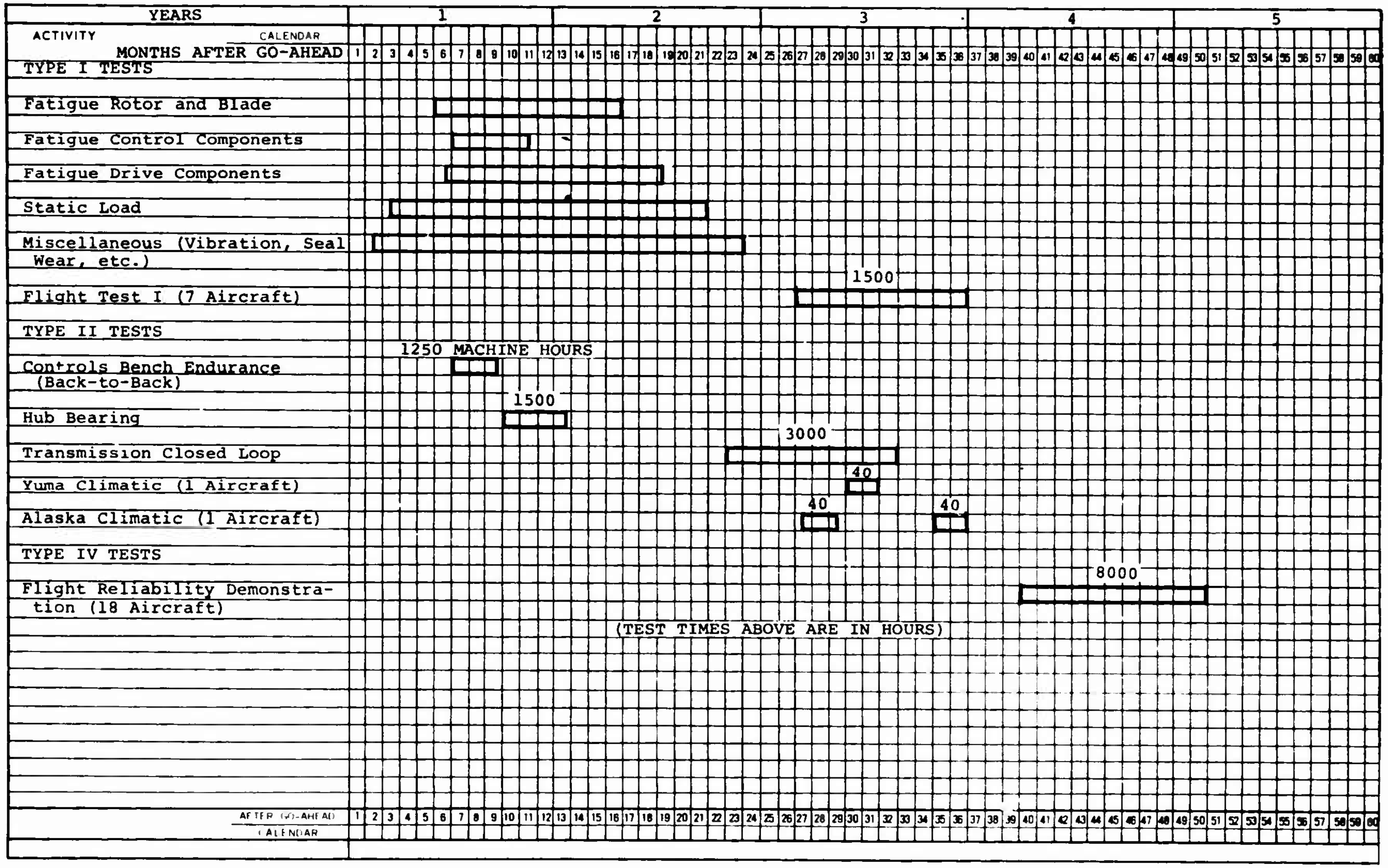


Figure 46. Helicopter "B" Test Plan Demonstrating 500-Hour MTBR*, 60% Confidence, 80% Probability of Passing Demonstration, and 3-Year Problem Identification Demo-Out.

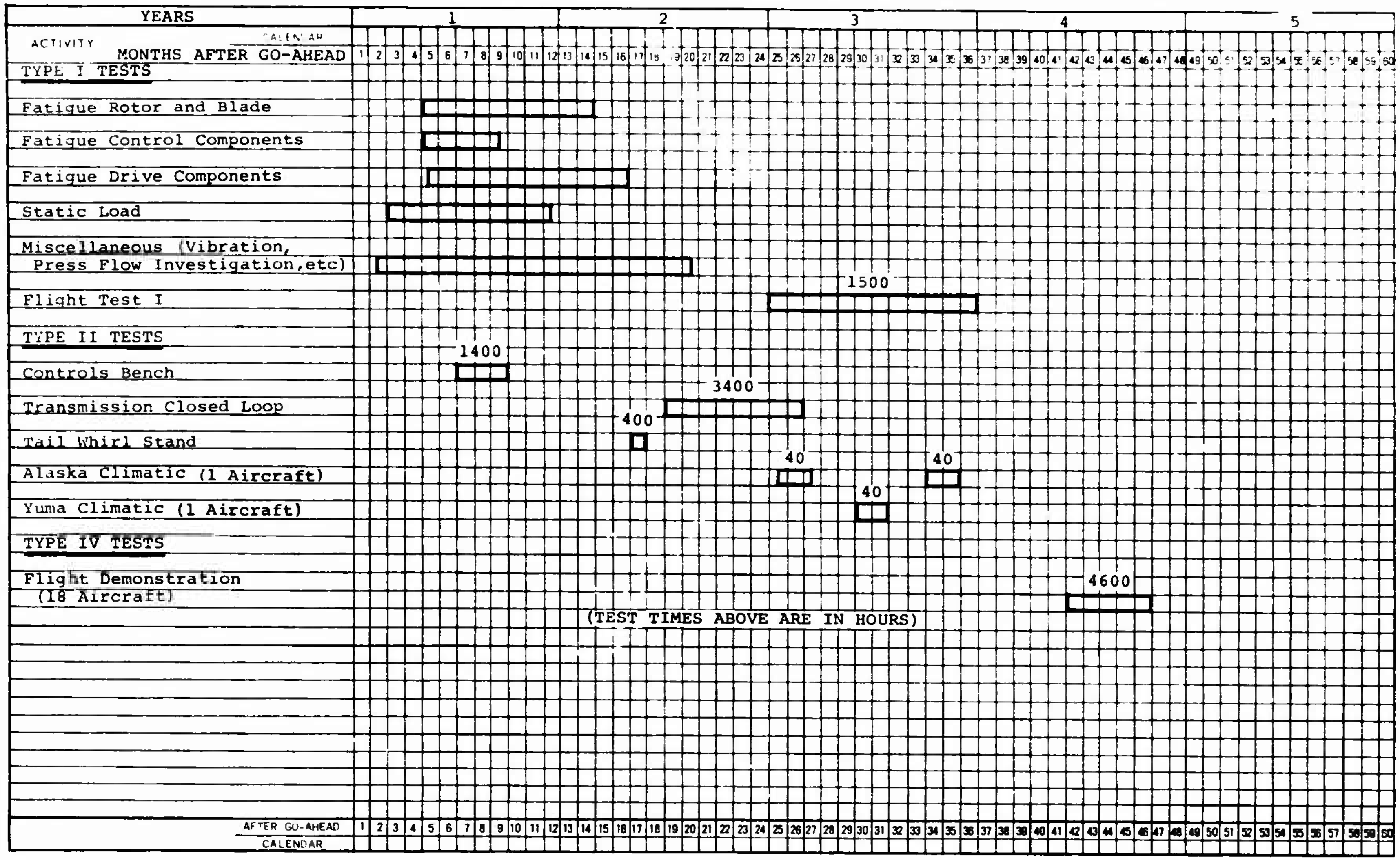


Figure 45. Helicopter "A" Test Plan Demonstrating 500-Hour MTBR*, 60% Confidence, 80% Probability of Passing Demonstration, and 3-Year Problem Identification Demo-Out.

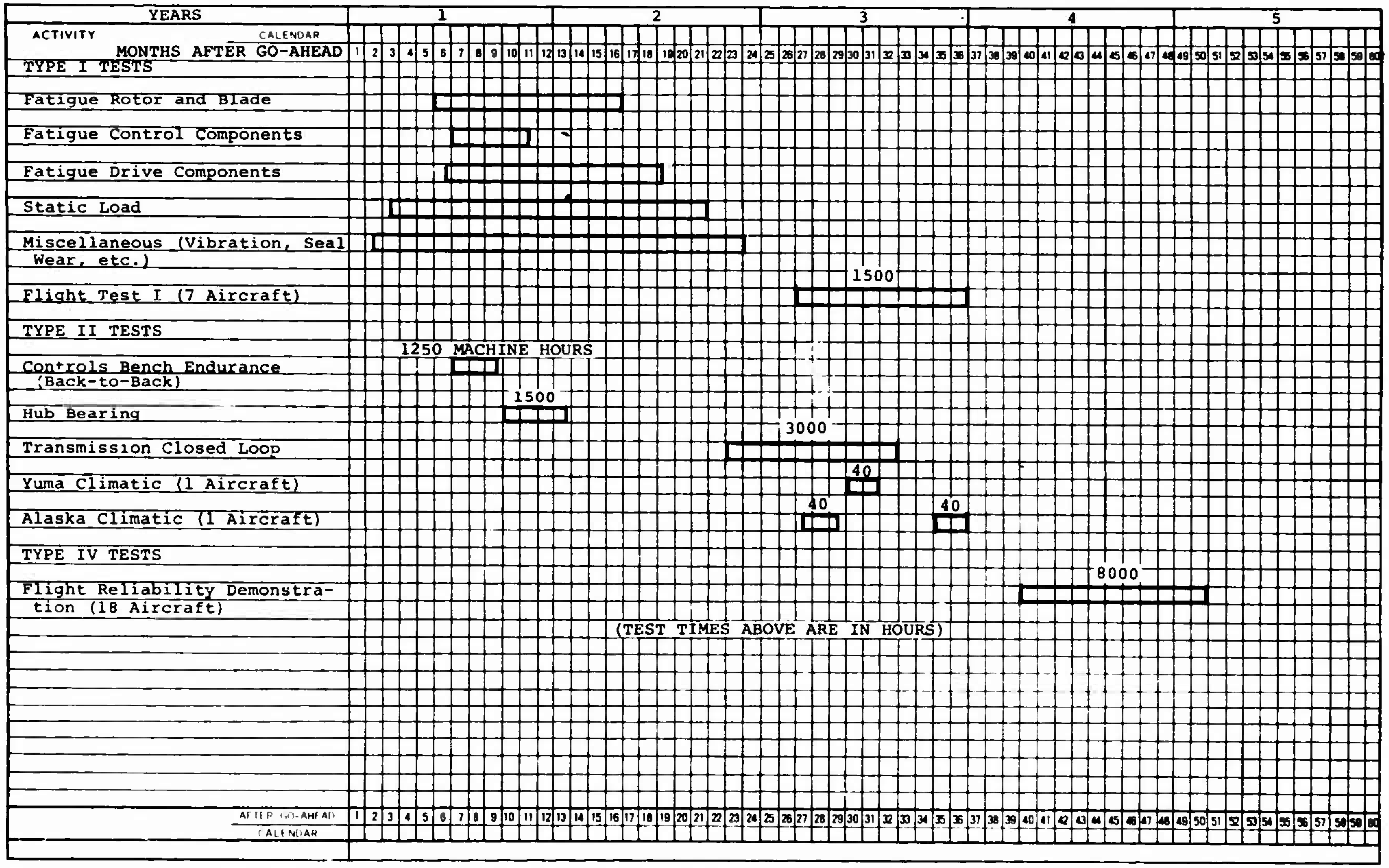


Figure 46. Helicopter "B" Test Plan Demonstrating 500-Hour MTBR*, 60% Confidence, 80% Probability of Passing Demonstration, and 3-Year Problem Identification Demo-Out.

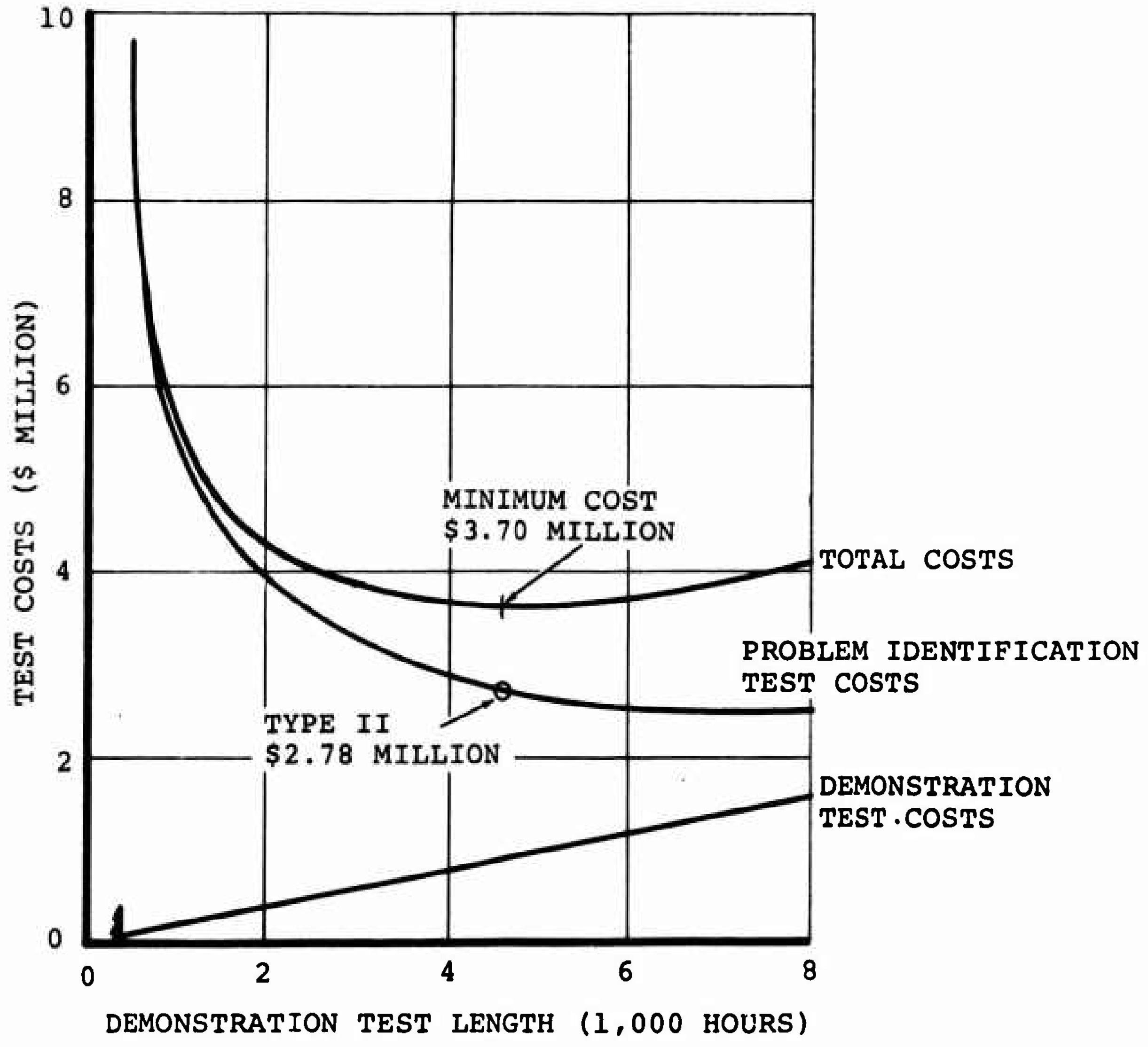


Figure 47. Cost Optimization for Helicopter "A" Problem Identification Demonstration Tests (500-Hour MTBR*, 60% Confidence, and 80% Probability of Passing Demonstration).

Type II Tests (and hours)	Number of Specimens		Cost ($ million)
Controls Bench Endurance, Back-to-Back (1,400)	3		0.15
Transmission Closed Loop (3,400)	2		2.26
Tail Whirl Stand (400)	2		0.37
		Subtotal	2.78
Alaska Climatic (80)			0.20
Yuma Climatic (40)			0.10
		Subtotal	3.08
Type IV Tests (and hours)			
Demonstration Tests (4,600)			0.92
		Total	4.00

HELICOPTER "B"

The Type I tests costs were previously estimated for Helicopter "B" and are given on Table XV. They are summarized as follows:

	Average Number of Specimens		Cost ($ million)
Fatigue, Rotor Components	9		4.19
Fatigue, Control Components	8 (Includes 2 hogouts)		0.93
Fatigue, Drive Components	10		3.10
Static Load	2		0.46
Miscellaneous			0.48
		Subtotal	9.16
Flight (1500 flight hours at $26,000 per hour)			39.00
		Total	48.16

The Type II tests, as for Helicopter "A", are most economically performed at the required MTBR level with bench test programs. A formal trade-off between problem identification and demonstration costs was not performed for Helicopter "B", but an optimum demonstration length of 8,000 hours was projected, reflecting the higher costs of problem identification for Helicopter "B" (with Helicopter "B" demonstration costs per flight hour equal to those of Helicopter "A", which is true for demo-out conditions only, where demonstration costs charged to developmental funds represent only the cost of data acquisition and analysis). At this 8,000-hour demonstration length for Helicopter "B", the required MTBR is approximately 620 hours, somewhat lower than the 720 hours for Helicopter "A".

The 1,500 hours of Type I flight testing are sufficient to achieve this required MTBR on the rotor blades, rotor hub and drive shafting. An additional test technique is required, however, over Helicopter "A" for the elastomeric hub bearing currently proposed for Helicopter "B". Also, the tandem configuration results in a more complex closed loop transmission test stand. The Type II costs are summarized as follows:

Type II Tests (and hours)	Number of Specimens		Cost ($ million)
Controls Bench Endurance, Back-to-Back (1,250)	3		0.28
Hub Bearing (1,500)	3		0.19
Transmission Closed Loop (3,000)	2		8.72
		Subtotal	9.19
Alaska Climatic (80)			0.37
Yuma Climatic (40)			0.18
		Subtotal	9.74
Type IV Tests (and hours)			
Demonstration Tests (8,000)			1.60
		Total	11.34

The distribution of costs among Type I, II, and IV testing for both Helicopters "A" and "B" suggests an underemphasis of reliability. The 720- or 620-hour required MTBR's are not particularly challenging; in fact, the 1,500-hour Type I flight testing is adequate to achieve the MTBR requirement on the main rotor blades and rotor hub so that no main whirl tower is required on either program. The individual test techniques do not consume a period of time approaching the full 3 years, which suggests that more aggressive programs are appropriate.

SIZE, WEIGHT, AND CONFIGURATION EFFECTS

Variables that can have a significant effect on the cost of the total program are the size, weight, and configuration of the aircraft being developed. This was recognized in estimating the Type I and II test costs for Helicopters "A" and "B", which represent extremes of size, weight, and configuration. Test costs were constructed considering the specific helicopter designs and their influence on component acquisition costs, horsepower/torque requirements, and test complexity.

To assist in predicting future anticipated effects of size, weight, and configuration, each test type is discussed separately.

Type I Ground Tests

In retrospect, the sum of Type I test costs (Table XV) has a definite correlation with the gross weight of the aircraft. Figure 48 shows this trend and also presents the separate contributions of the prime elements: fixtures, specimens, and operations. These elements are examined in detail in the following paragraphs.

Fixtures

The increase in total fixture costs (with gross weight) is primarily due to the rotor blade fixture. Since nearly each new blade design requires a newly designed and fabricated fixture, there is little use of existing equipment. Costs for these fixtures are driven both by the size of the blade and the type of fixture used. A resonant beam technique was used for the CH-47 and is projected for Helicopters "A" and "B". Use of other more "brute force" techniques could escalate the costs manyfold. For components other than the blade fixture, costs usually include the mounting structure and control/instrumentation added to a basic fatigue machine, and are a rather small cost element. The total number of different components requiring test has a multiplying effect upon fixture costs, and is a function of the aircraft configuration. Designs which use similar components in duplicate applications (e.g., tandem-rotor configuration) have a slight cost advantage over those requiring more specialized components (such as the tail rotor system on a single main rotor aircraft). This effect may contribute to the relatively small cost difference noted between the single-rotor Helicopter "A" and the CH-47.

Operating Costs

Power costs are less than 1 percent of total Type I ground test costs; hence, the effects of increased component size and weight are minimal. Labor is the key element here, in terms of engineering and manufacturing support, and is influenced by the complexity of the test loads (directions, magnitudes, method of application and control) and the sheer number of components tested. The above fixture comments concerning aircraft configuration are again applicable.

Specimens

Total specimen costs are a function of the number of units required and their individual acquisition costs. The number of specimens per component tested was maintained at a fixed value equalling the number tested during the first

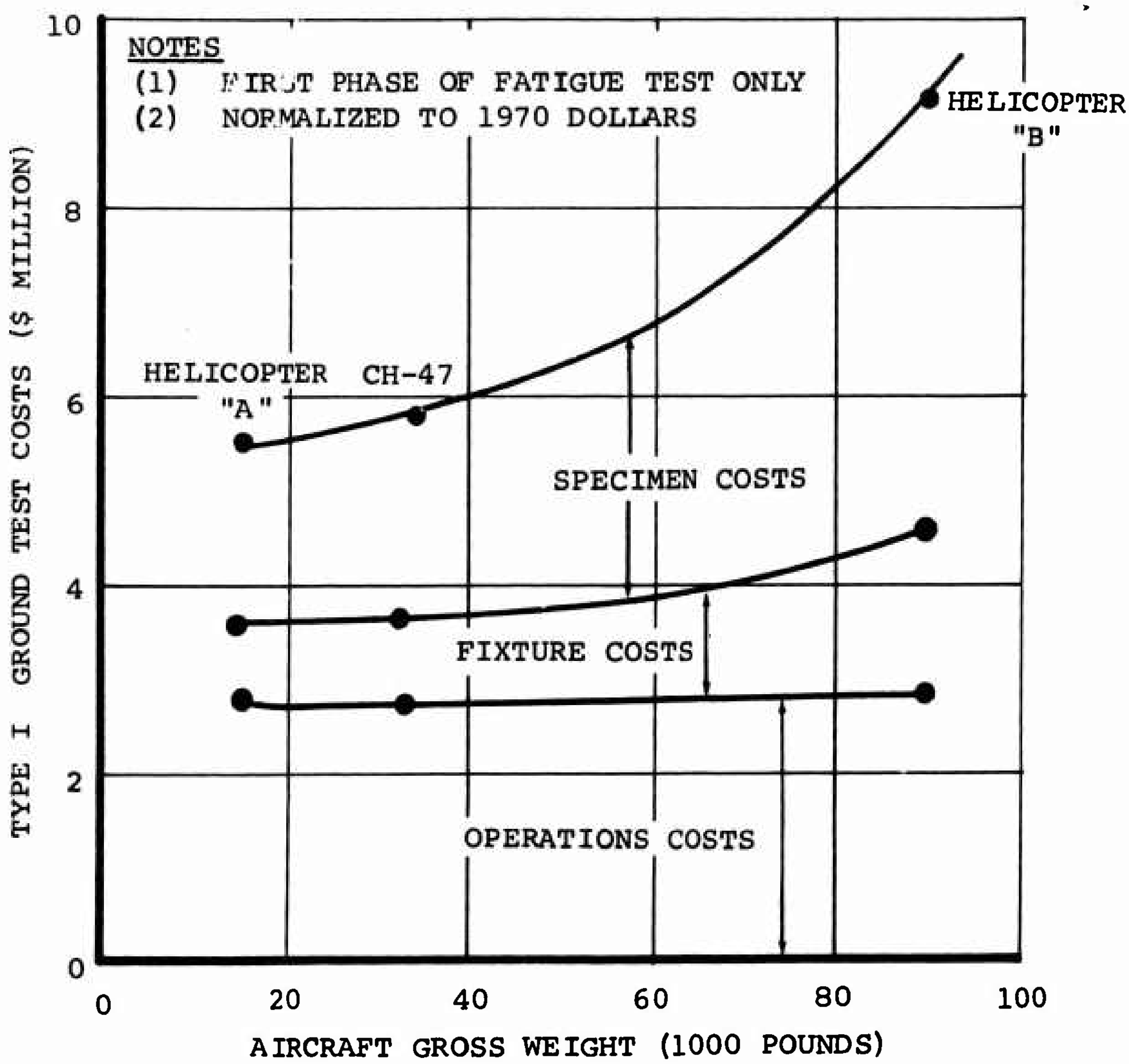


Figure 48. Effect of Aircraft Gross Weight on Trend of Type I (Design Development) Ground Test Costs.

phase of the CH-47 fatigue program. The large increase in specimen costs from Helicopter "A" and the CH-47 to Helicopter "B" is due mainly to the increased acquisition cost of Helicopter "B" specimens. The effect of size and configuration on acquisition cost is complex and beyond the scope of this study. It is, however, the most significant factor in Type I ground test costs.

Type I Flight Testing

Flight test costs respond to different factors than do ground test costs. Over 80 percent of the costs consist of engineering and manufacturing labor support of the program. The remaining costs consist of POL, spares, flight crew, etc. Labor costs were predicted for Helicopters "A" and "B" as well as for the CH-47 using trend curves driven by the weight of the aircraft.

Type II Tests

To quantify the cost impact of size, weight, and configuration on Type II tests, the costs of the sample plans are compared for Helicopters "A" and "B". A breakdown of these costs into separate elements for the required 600-hour MTBR is as follows:

	Costs ($ Million)			Increase of
Element	Helicopter "A"	Helicopter "B"	Difference	"B" Over "A" (%)
Fixtures	1.2	5.4	+4.2	450
Specimens	0.2	1.5	+1.3	750
Operations	0.7	2.3	+1.6	330
Total	2.1	9.2	+7.1	440

The largest cost impact (in terms of absolute costs) is in the fixtures element. Fixture costs in Type II tests are a function of both the configuration and size of the helicopter. Of the $5.4 million shown for Helicopter "B" fixtures, approximately $5.2 million is for the transmission closed loop rigs. These fixture costs are influenced by the addition, on Helicopter "B", of a combining and two engine transmissions, and the increased power requirements. The most dramatic change from "A" to "B" (in terms of percentages) was in the specimen cost elements. Here, size is the most important variable. However, this cost element had the smallest absolute value increase.

The previous cost display was for a low required MTBR (600 hours) program. At a higher required MTBR (5200 hours), the cost

breakdown for Helicopter "A" is somewhat different. A comparison with the 600-hour required MTBR program is as follows:

Element	Type II Costs for Helicopter "A" ($ Million)	
	600-Hour Required MTBR	5200-Hour Required MTBR
Fixtures	1.2	2.5
Specimens	0.2	0.7
Operations	0.7	4.4
Flight Test	-	15.0
Costs	2.1	22.6

In the 5200-hour required MTBR program, the cost of operations has risen nearly sevenfold and is now 60 percent of the total ground test cost. However, flight testing now dominates the total when added at this required MTBR value (see Figure 49). Operating costs of flight aircraft performing Type II objectives are best described as a function of weight (Figure 1); therefore, size and weight should be more significant than configuration at higher required MTBR levels.

In summary, the costs of Type I and II testing appear more sensitive to size and weight than to configuration.

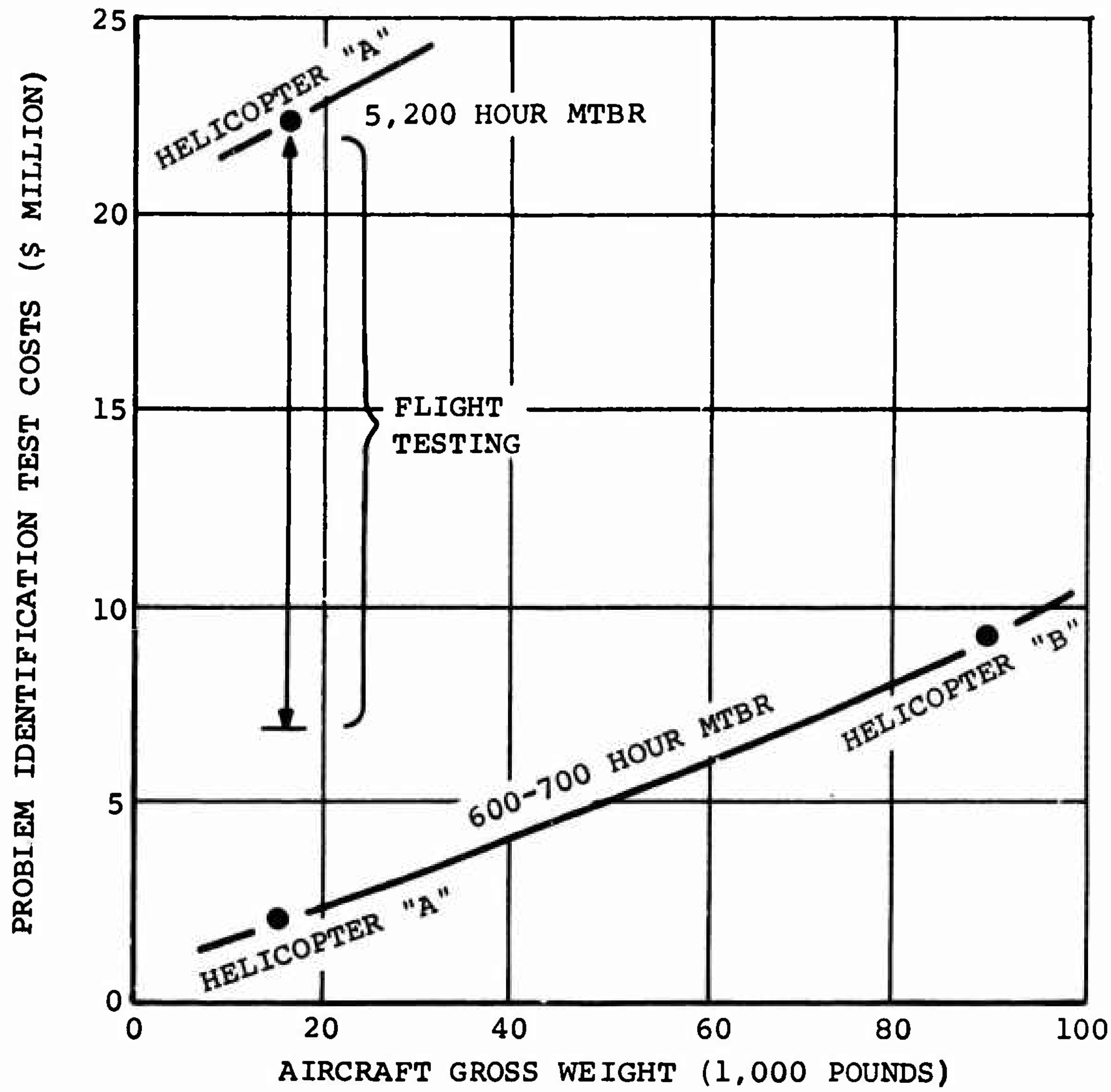


Figure 49. Effect of Aircraft Gross Weight Upon Problem Identification Costs.

9. MILITARY SPECIFICATION REVIEW

Based on the results of the study, the Military specifications listed in Table XVIII were reviewed to identify changes that would enhance the possibility of achieving more reliable components. It is generally accepted that certain activities are essential to the achievement of a reliable product. Hence, these Helicopter and Helicopter Component General Design and General Test Requirements Specifications were reviewed to determine the degree to which the following essential activities were considered:

1. Establishment of a numerical reliability requirement

2. Definition of "success" from the standpoints of reliable equipment functioning and permissible levels of degradation

3. Definition of service environment extremes

4. Definition of required testing to demonstrate achievement of the numerical reliability requirement under defined environmental conditions

Table XVIII tabulates the reliability-oriented requirements present in these specifications. In general, these specifications have not established numerical reliability requirements, the test requirements necessary to achieve them, or the demonstration requirements necessary to prove achievement. While TBO requirements and fatigue life requirements are reliability-oriented and may have dramatic effects upon part reliability, they are not in themselves acceptable numerical measures of hardware reliability. Appropriate measures would be:

1. Probability of success, for a designated duration

2. Mean time between failures (or the reciprocal "failure rate")

3. Mean time between removals, or mean time between unscheduled removals (or reciprocals thereof. expressed as rates)

The next step was to consider potential specification changes. Since the contract study effort showed that reliability requirements would have significant impact on schedule and development test costs, it correspondingly could be concluded that schedule requirements and available developmental dollars could exert significant influence on the hardware reliability requirements stated by a customer. It follows then, that the

TABLE XVIII. SUMMARY OF REVIEW OF MILITARY SPECIFICATIONS FOR HELICOPTER DYNAMIC SYSTEM RELIABILITY REQUIREMENTS

Specification	Summary of Reliability Oriented Requirements
MIL-S-8698, Add. I, 28 February 1958 Structural Design Requirements Helicopter	Defines or provides methodology for determining design loads, stress, and safety factors for all components. Requires "minimum fatigue life of 1000 hours" for "the helicopter and its components".
MIL-F-9490C, Add. I, 9 March 1966 Flight Control Systems, Design, Installation, and Test of, General Specification For	Contains design specifications, including 1000-hour TBO objective, 2-million cycle life objective for manual system, 5-million cycle life objective for AFCS, and a requirement to assign an MTBR objective. Requires AFCS 1000-hour life test (no servicing first 200 hours), environmental tests per MIL-STD-810 and reliability tests per MIL-R-26667.
MIL-T-8679 5 March 1954 Test Requirements, Ground Helicopter	Defines static test requirements for rotor control and transmission mounts, fatigue test of rotors and blades, and whirl and tiedown tests. Specimen quantities, types of loads and duration are generally specified. Submits plan for transmission bench test. Provides details of transmission acceptance tests.
MIL-A-8064B 22 January 1970 Actuators and Actuating Systems, Electromechanical, General Requirements For	Contains general requirements and guides for preparing detail specifications. Environmental tests per MIL-STD-810. MIL-STD-785 Reliability Program imposed. Tests in accordance with MIL-STD-781.
MIL-T-5955B 5 June 1961 Transmission Systems, VTOL-STOL General Requirements For	Contains general and detail design requirements including specification of anticipated environments. Specifies 1000-hour transmission "life without replacement". Requires testing per MIL-T-8679 and production acceptance tests.

TABLE XVIII - CONTINUED

Specification	Summary of Reliability Oriented Requirements
MIL-C-5503C, Add. 3, 9 March 1966 Cylinders, Aeronautical, Hydraulic Actuating, General Requirements For	Contains general design specifications. Design required to pass specific tests, including proof, burst, leakage, immersion, inspection, and temperature, plus endurance of 2 or 5 million cycles. Packing changes permitted every half-million cycles.
MIL-H-5440E, Add. I, 2 December 1966 Hydraulic Systems, Aircraft, Types I and II, Design, Installation, and Data Requirements For	Design and installation practices-oriented. Requires MIL-Spec accumulators valves, etc. Air Force requires "data per MIL-STD-785".
MIL-T-5522C 25 March 1966 Test Procedure for Aircraft Hydraulic and Pneumatic Systems, General	Performance tests of hydraulic and pneumatic systems, all performed on the aircraft. Measure pressure and temperature. Assure smooth and positive movement. Preflight and flight functional test.
MIL-E-5272C 20 January 1960 Environmental Testing, Aeronautical and Associated Equipment, General Specification For	"Procedures" specification for environmental testing of aeronautical equipment. Tolerances are specified. Generally accelerated tests.
MIL-D-23222C 27 May 1963 Demonstration Requirements for Rotary Wing Aircraft (Helicopters)	General contractor demonstration requirements to show aircraft safe to operate to envelope limits. Flight testing includes 250 hours endurance, plus various performance, stress and vibration surveys.

concept of stating specific reliability requirements in the general specifications reviewed may be totally inappropriate.

Nevertheless, the study results indicate the importance of relating reliability requirements, test programs and demonstration, and it appears desirable to formalize these relationships within some development program specification framework. Further, since various "levels" of reliability may be appropriate for certain hardware items (based on schedule and available development dollar considerations), it appears appropriate to define formal techniques for planning test and demonstration programs, with the reliability requirement as an independent variable.

A proposed specification arrangement that would supplement existing documents to accomplish the desired objective has accordingly been outlined, and is represented schematically in Figure 50. Simply stated, the proposed specification revisions consist of:

1. Deletion of reliability objectives and requirements from current general design specifications

2. Generation of reliability handbooks with candidate reliability test program elements

3. Requirements that appropriate elements shall be included in a reliability plan

A description of the detailed changes required to implement this arrangement is presented in the following paragraphs.

REVIEW OF INDIVIDUAL SPECIFICATIONS

Detail Model Specification of the XXX Helicopter

The detail specification should include specified reliability requirements and criteria selected from, and described in detail by, a new "Handbook of Candidate Reliability Levels and Criteria". A reliability program plan may be required. with the format per MIL-STD-785. The reliability development testing should be guided by a new "Handbook of Reliability Development Test Planning and Costs". The demonstration testing should be selected, as appropriate, from MIL-STD-781 type documents.

Handbook of Candidate Reliability Levels and Criteria

Levels of reliability are established in a manner similar to the levels for electronic components. For example, MIL-STD-217 Level M is 10 failures per million hours, Level N, 1 failure per million hours. The handbook would typically

express MTBR levels of 500, 1,000, 1,500 and 2,000 hours, with various confidence levels. Since industry has not agreed on a single expression of reliability, the handbook could also define levels of reliability in terms of mission reliability, malfunction rates, removal rates, and depot returns.

The criteria concerning "relevant incidents" and "creditable time" should be defined as related to maintenance and TBO philosophy, maintenance-induced malfunctions, manufacturing and material defects, convenience and precautionary removals, crash and combat damage, and removals to facilitate maintenance. The statistical methodology would be defined for various failure frequency distributions, including the treatment of pattern failures and dependent failures.

MIL-T-8679 Test Requirements, Ground, Helicopter

Numerical reliability inferred references should be deleted. Safety of flight oriented numerical values for test type and duration should remain in the specifications.

General Design Specifications (MIL-T-5955, MIL-S-8698, MIL-F-9490)

Numerical reliability inferred references should be deleted. Safety of flight oriented numerical design objectives should remain. Appropriate environmental tests per MIL-STD-810 should be specified.

MIL-STD-810 Environmental Test Methods

Operational sand and dust tests should be added to the specification.

MIL-STD-785 Reliability Program for Systems and Equipment Development and Production

The specification is basically unchanged. Additional references should be added for the new "Handbook of Reliability Levels and Criteria" and "Handbook of Reliability Development Test Planning and Costs".

Handbook of Reliability Development Test Planning and Costs

The purpose of the handbook is to present baseline information as an aid in structuring programs. Reliability development plans and their related costs are provided. Nonrecurring and recurring industry average costs are presented as functions of measured variables. Historical reliability improvement data for various test durations are presented for helicopter components.

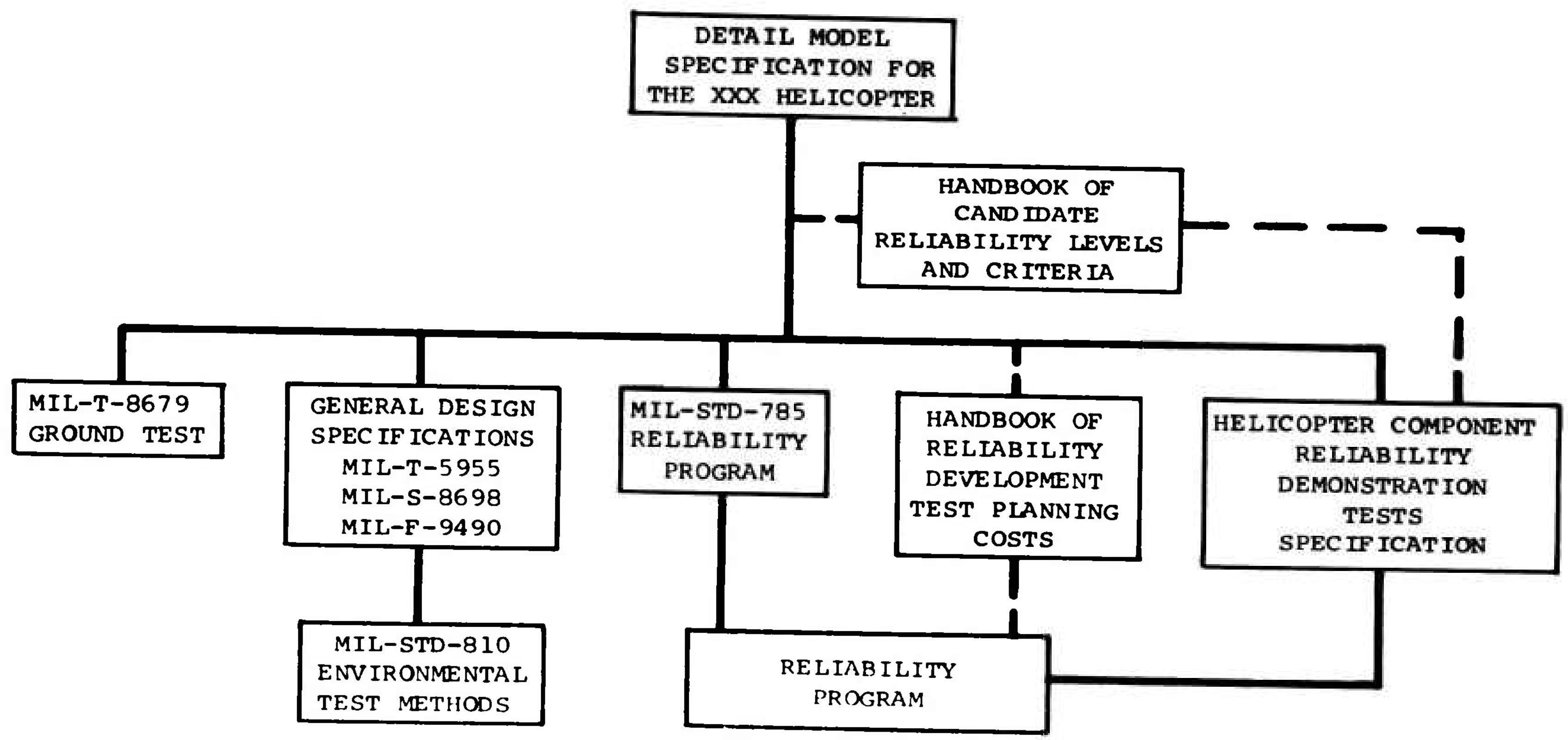


Figure 50. Schematic of Proposed Specification Revision Procedure.

Helicopter Component Reliability Demonstration Test Specification

A document similar to MIL-STD-781 should be written for helicopter drive and rotor components. Test severity levels should be cited, with test inputs such as power replacing the voltage inputs of MIL-STD-781. In addition to the sequential testing and exponential distribution of MIL-STD-781, other failure distributions should be combined with sequential and nonsequential testing to formulate candidate demonstration schemes.

SUMMARY

The recommended Military specification revisions outline a method for the structuring of reliability test programs. The details of the method are deemed beyond the limitations of this contract. Examples of the details requiring additional study efforts include: Establish minimum safety of flight requirements, and establish reliability demonstration tests similar in format to MIL-STD-781.

10. CONCLUSIONS

Many aspects of testing and reliability growth were considered in this analysis. Results of the analysis and apparent conclusions have been discussed in the appropriate sections. This section concentrates, therefore, on only those major conclusions that merit repetition.

TEST OBJECTIVES AND TYPES

- To analyze the cost-effectiveness of complete aircraft test programs, the specific objectives of various types of developmental tests must be considered and defined. Certain types of tests are a direct function of numerical reliability requirements; others are not. Evaluation or prediction of test costs or productivity must acknowledge each respective test objective, the specific aircraft under test, and overall program goals.

PROBLEM IDENTIFICATION TEST EFFECTIVENESS

- Historical data of problem detection during tests indicated that many problems were not detected during tests because of artificial restraints; that is, limitations existed which were unrelated to the actual test hardware (e.g., specimens, loads, and fixtures). These restraints must be eliminated in future programs to maximize test productivity. The realistic evaluation of relative effectiveness of test techniques also requires elimination of these artificial restraints.

- The use of overload testing cannot reduce test duration significantly until the relationships between failure rates (MTBF) and applied load/environments are more thoroughly understood. The necessity for test validity (belief in the results) dictates that realistic load/environments, rather than overloads, be applied during the test.

EVALUATION OF ALTERNATE TEST TECHNIQUES

- Comparison of the cost-effectiveness of individual test techniques can only be performed when the alternate techniques test the same components and have relatively similar cost, schedule, and effectiveness characteristics. For all other test techniques, complete test programs must be constructed and costed.

- The existing test facilities of the contractor performing the program must be considered in selecting the appropriate test techniques.

- The optimum mix of techniques depends upon the desired MTBR and the elapsed time of the program. For very low or very high MTBR's and short elapsed times, the bench type programs cost less. At intermediate values of MTBR and longer elapsed times, the dynamic system test type programs cost less.

- The optimum mix of techniques also depends upon the MTBR desired for each component. If each component has the same MTBR goal, the test techniques which test all components for the same duration (dynamic system test, tiedown, flight test) have a cost disadvantage in that they "overtest" some components. A more comprehensive analysis, which includes a life cycle cost benefit of the MTBR for each component, provides a more equitable optimization and indicates that DST type programs have equal or less costs than bench tests.

INITIAL OR OFF-THE-BOARD RELIABILITY

- The off-the-board MTBR or the aggregate of the failure modes in the component before entering problem identification tests defines, along with test effectiveness, the duration required to achieve a given MTBR from the test program. More important than the absolute MTBR value are the failure mode distributions of the components, which ultimately drive the required test durations. Efforts to reduce test time (or improve the resultant MTBR) by improving this off-the-board MTBR should give the same attention to the low and medium frequency problems that is currently given to high frequency problems.

DEMONSTRATION TESTING

- By themselves, test results of problem identification tests cannot provide numerical demonstration that a contractual requirement has been satisfied. This is because the changing configuration precludes adequate statistical treatment of test results.

- An effective means of reducing total costs is to vary the duration of the demonstration test so that, in combination with problem identification tests, a minimum total cost is achieved.

- For formal and separate demonstration tests, two approaches are proposed: a development-funded early demonstration and a late O&M-funded demonstration (demo-in and demo-out). Of the two, the demo-out has significantly less costs, especially for demonstration of higher levels of MTBR and confidence.

TEST PROGRAM COST VARIABLES

- Of the cost variables studied, the demonstration approach (demo-in or demo-out) and the reliability levels to be demonstrated have a greater cost impact than the mix of techniques used in the program or the elapsed time of the program.

- Preimplementation of component development can reduce test costs when the MTBR's are high or the basic program elapsed time is short. More importantly, preimplementation can reduce total life cycle costs by permitting more production units to incorporate corrective action resulting from the test program.

- Large percentages of total development test funds are expended on tests which do not vary as a function of MTBR objectives. These tests address the performance or safety levels of the aircraft.

- Large potential variations in test costs can result from the degree and nature of management control over the test program. One of the most critical aspects that must be controlled is the number of times that a failure mode must be detected before effective corrective action is implemented. All costs in this study have assumed an aggressive execution of the total test program. Inefficiency or unusual incompetence could magnify test costs by a factor of 8 to 10 times.

SIZE, WEIGHT AND CONFIGURATION

- Test program cost appears more sensitive to size and weight than configuration. For the problem identification portion only, configuration is more significant in the lower MTBR programs.

SPECIFICATION REVIEW

- Existing specifications which address numerical reliability or test durations do not reflect the relationships between these elements. Specifications that are to be generally applicable to all models should not contain specific numerical reliability or related test requirements. As appropriate, these requirements should be individually selected for each specific development program.

1. RECOMMENDATIONS

The following recommendations are made as a result of this study:

1. The establishment of test plans and resources for future helicopters should consider the cost and effectiveness factors discussed in this study. The specific objectives of the developmental test program should be integrated with overall program schedule and cost constraints for the purpose of achieving minimum test cost.

2. For current and future helicopter programs - reliability plans, test plans and Military specifications should be combined into a planned, comprehensive framework of documentation that reflects the relationship between test requirements and reliability objectives.

   This will involve modification of existing helicopter general design-test requirements specifications and creation of appropriate handbooks and specifications.

3. The specific objectives and requirements of test which are not determined solely by numerical reliability goals should be defined. Specifically, ground fatigue tests and flight test investigations contribute large portions to developmental test costs and require clarification of their ultimate objectives in precise terms in order to evaluate future program test cost requirements.

4. Further analysis should be conducted to quantify the relationships between failure rates and applied loads and environments on predominate or common failure modes in major dynamic components. This is required to effectively use accelerated or overload testing to reduce test costs and/or elapsed time.

5. This study optimized the problem identification and demonstration portions of developmental test costs against certain arbitrarily selected numerical reliability requirements. Proper consideration of aircraft total life cycle costs requires optimization of the numerical reliability level as well. It is recommended that additional studies be performed to:

a. Quantify the relationships between the actual MTBR, the design effort, and the acquisition costs necessary to achieve the MTBR.

b. Quantify the relationships between the actual MTBR and the O&M costs that result from this MTBR.

These additional studies must have specific program orientation in order to adequately formulate future product requirements that provide minimum life cycle costs.

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APPENDIX I

MAJOR DYNAMIC COMPONENTS OF THE CH-47

This appendix shows the assemblies on the CH-47 helicopter that were investigated in this study. Eight basic assemblies were analyzed:

1. Forward transmission (Figure 51)
2. Aft transmission (Figure 52)
3. Combining transmission (Figures 53 and 54)
4. Engine transmission (Figure 55)
5. Drive shafting (Figure 56)
6. Rotor controls (Figure 57)
7. Rotor head (Figure 58)
8. Rotor blades (Figure 59)

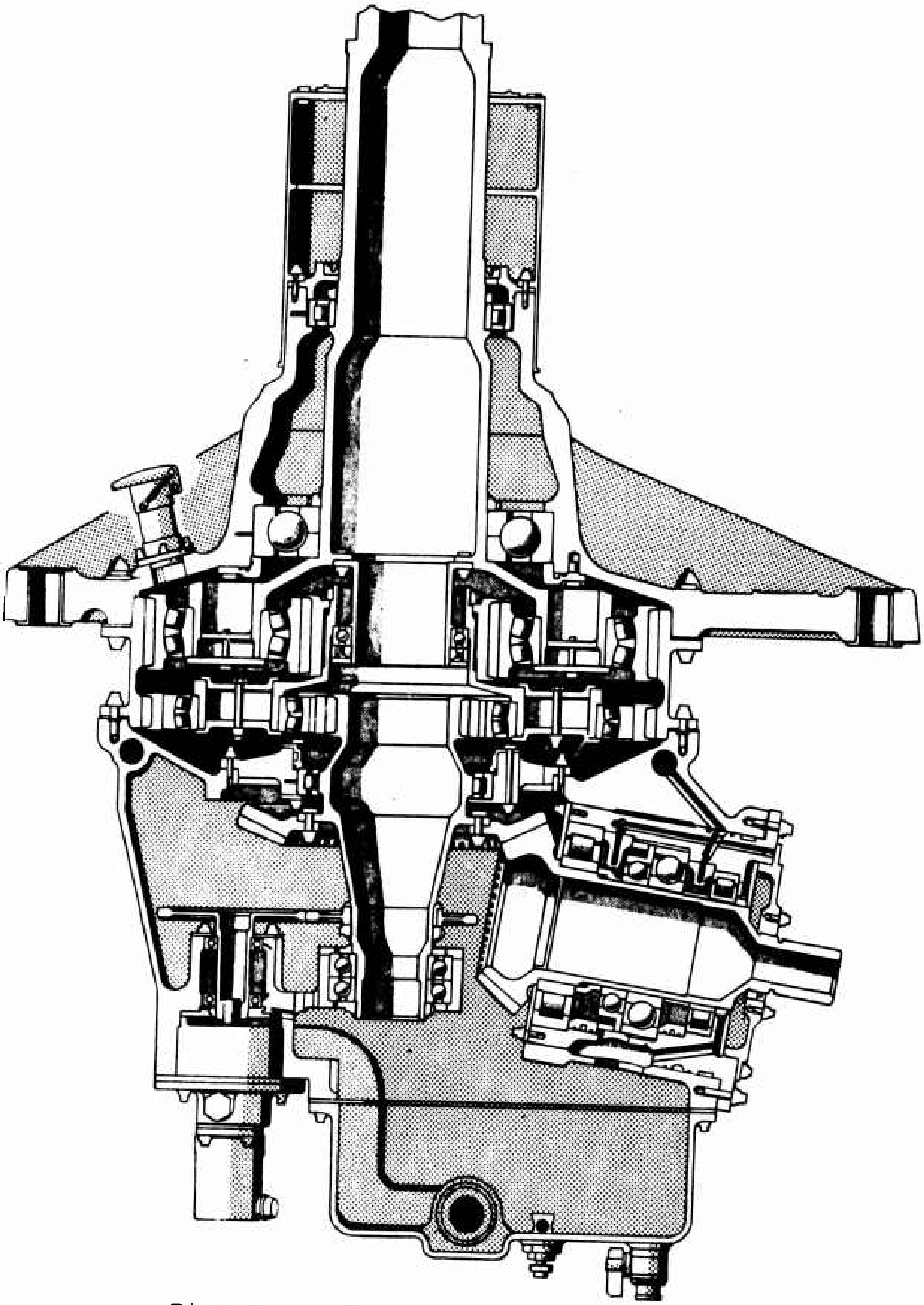


Figure 51. Forward Transmission.

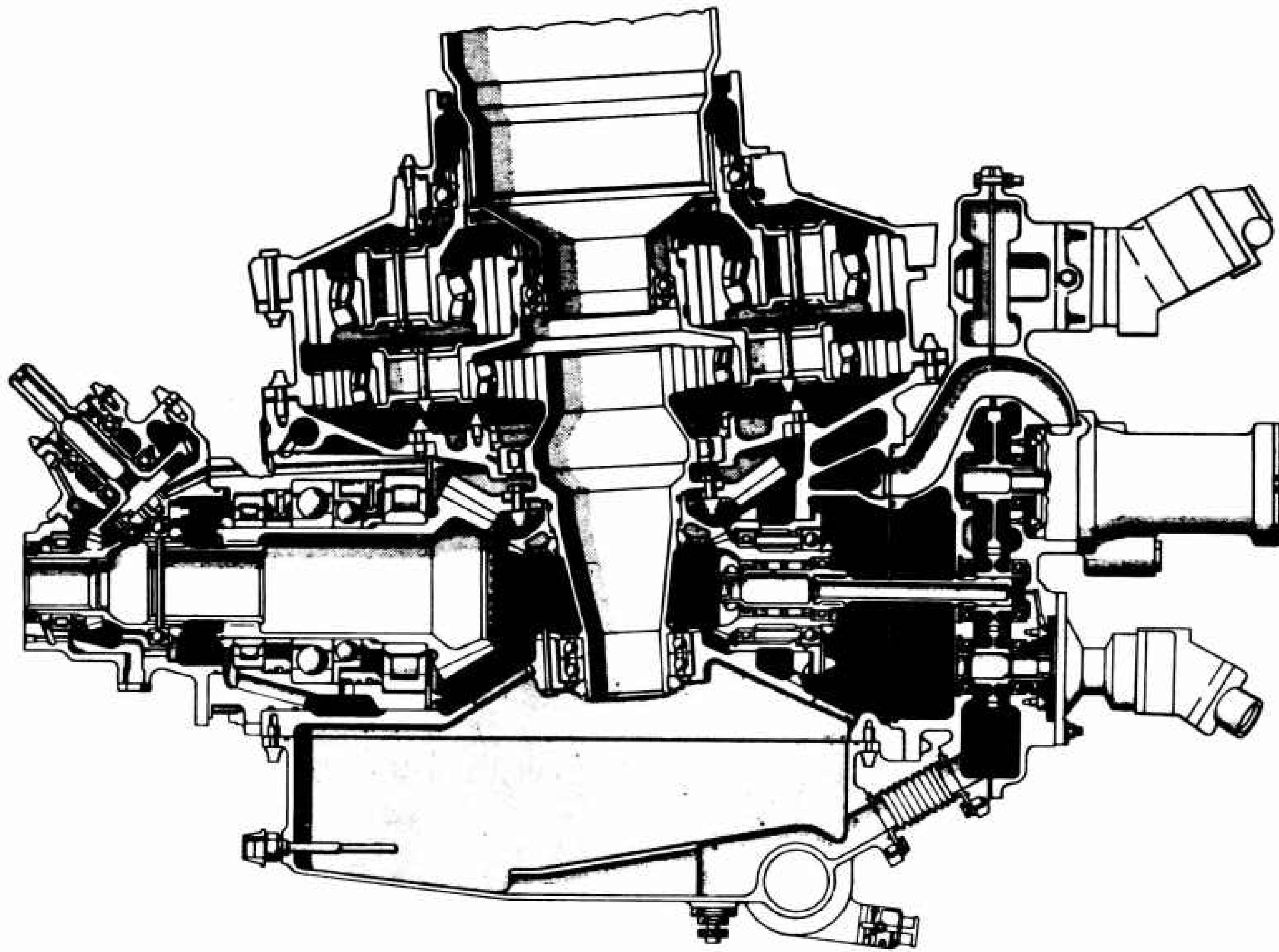


Figure 52. Aft Transmission.

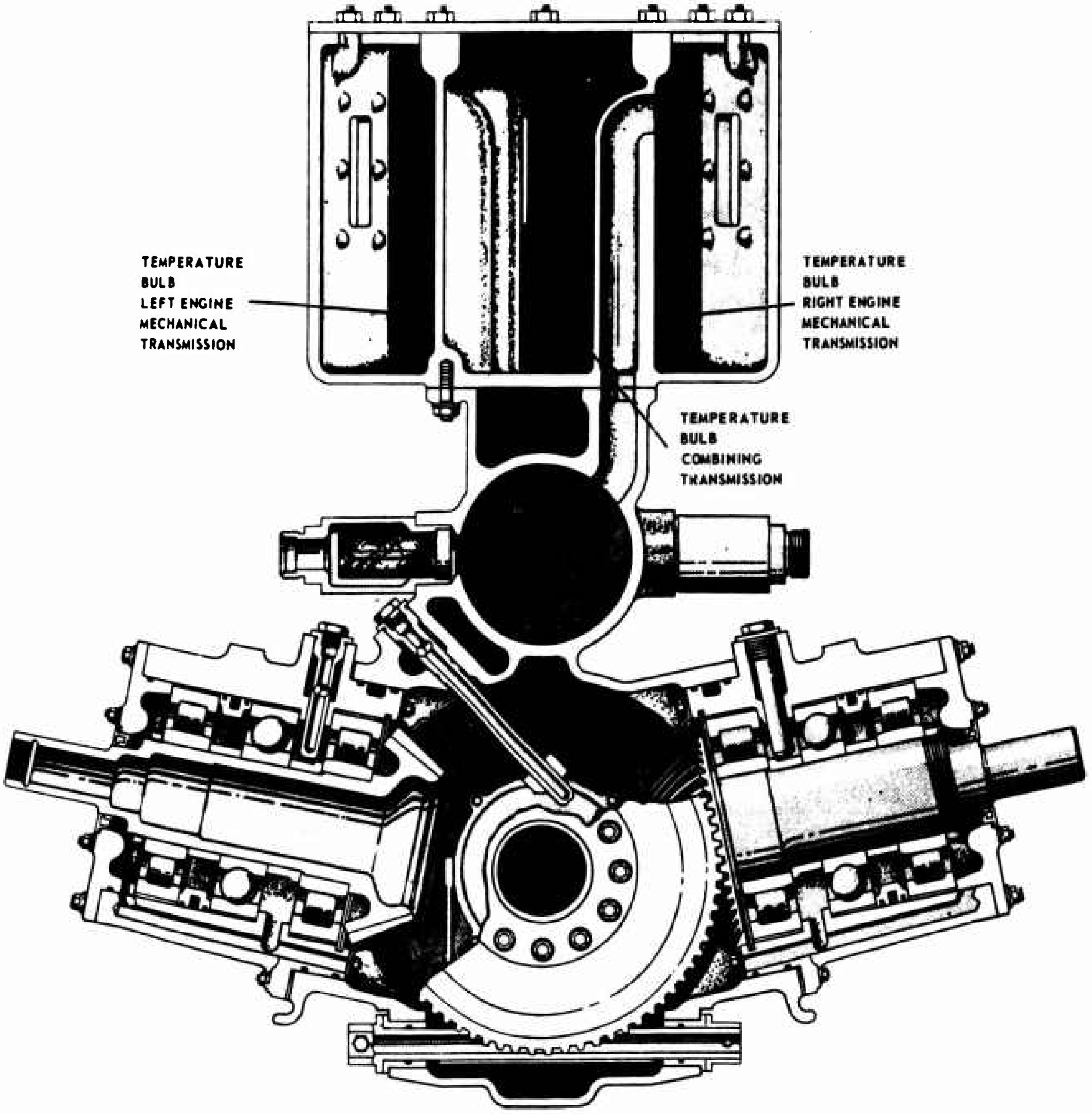


Figure 53. Combining Transmission.

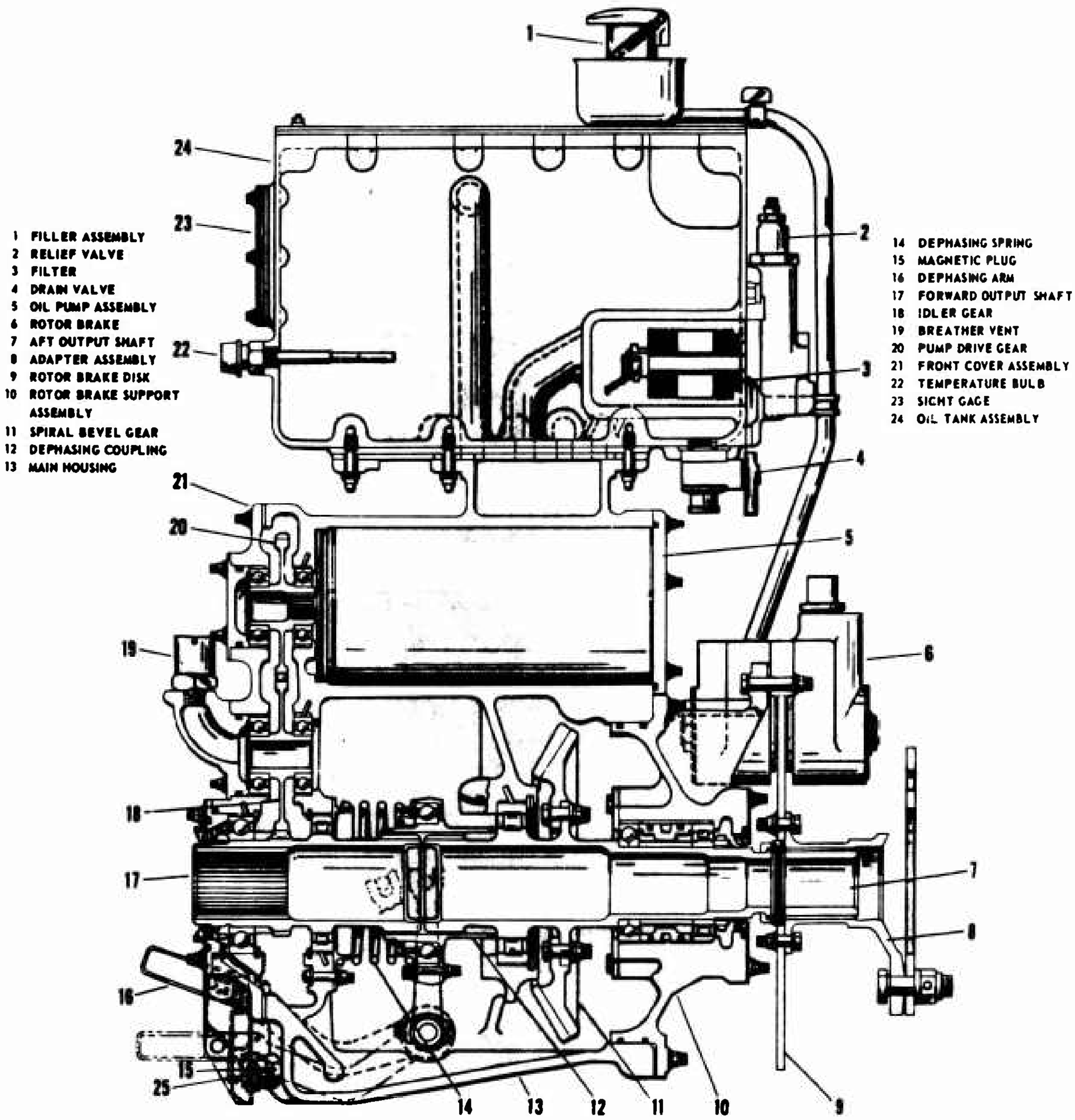


Figure 54. Combining Transmission.

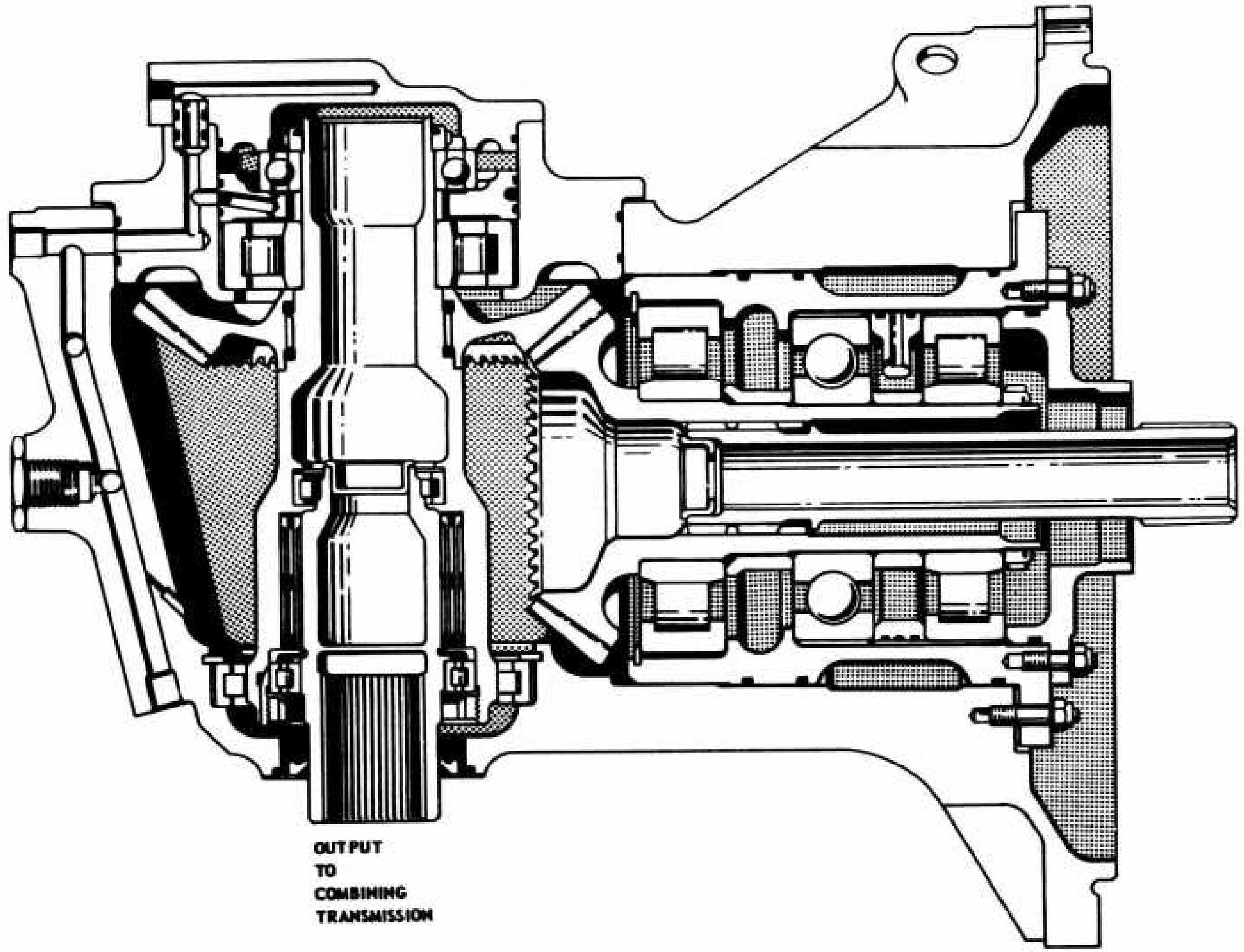


Figure 55. Engine Transmission.

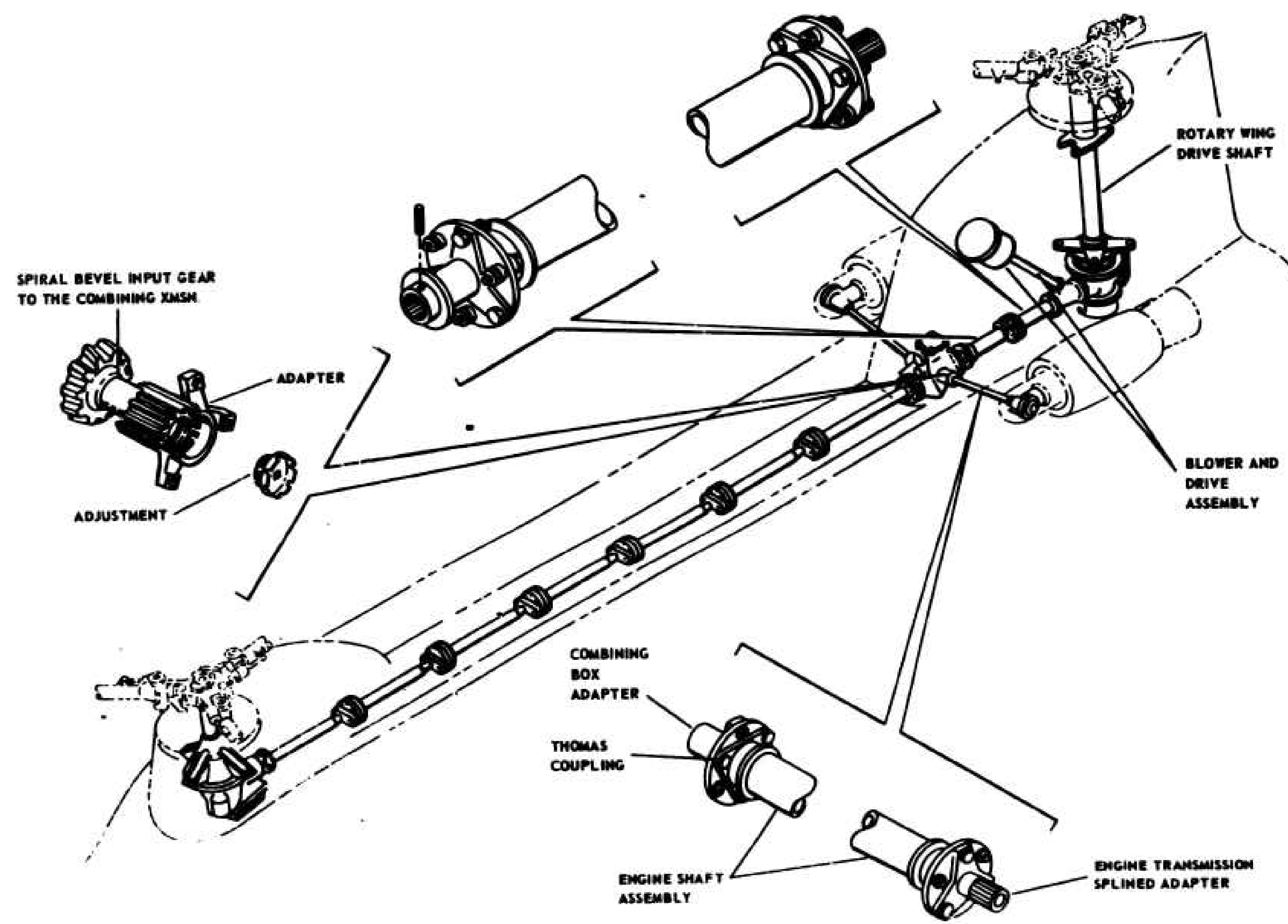
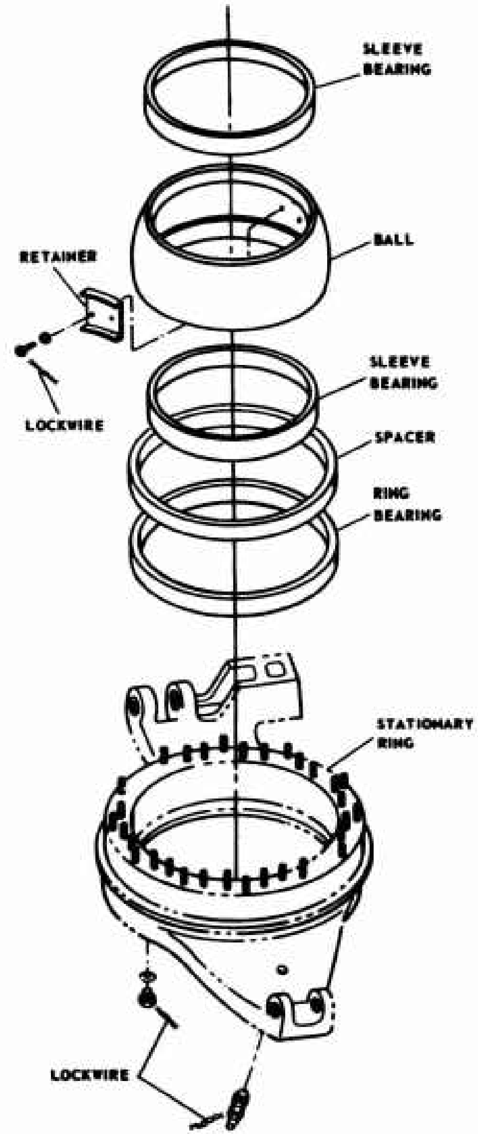
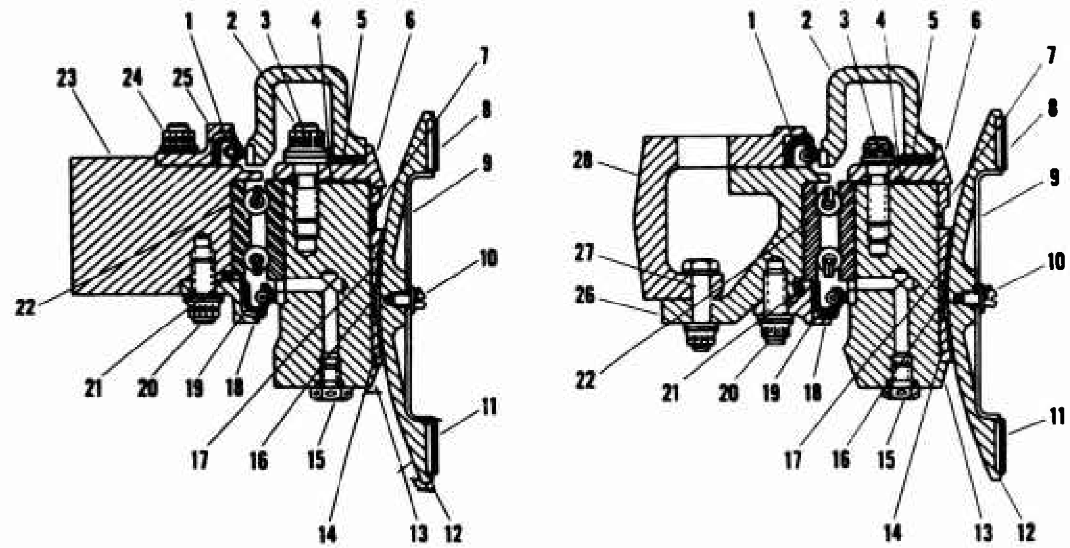


Figure 56. Drive Shafting.





1 UPPER OIL SEAL
2 OIL TANK
3 UPPER RETAINER NUT
4 PREFORMED PACKING
5 OIL TANK GASKET
6 UPPER RETAINER
7 RETAINING SPACER
8 UPPER SLIDING SLEEVE BEARING
9 SLIDING SLEEVE BEARING RETAINER
10 SCREW
11 LOWER SLIDING SLEEVE BEARING
12 BALL SPHERICAL BEARING RING
13 STATIONARY INNER RING ASSEMBLY
14 LOWER SPHERICAL BEARING (MATCHED SET)
15 OIL DRAIN PLUG
16 SPHERICAL BEARING SPACER
17 UPPER SPHERICAL BEARING (MATCHED SET)
18 LOWER OIL SEAL RETAINER
19 LOWER OIL SEAL
20 LOWER SEAL RETAINER NUT AND WASHER
21 PREFORMED PACKING
22 SWASHPLATE BEARING
23 OUTER RING (ONE-PIECE MACHINED TYPE)
24 UPPER SEAL RETAINER NUT AND WASHER
25 UPPER OIL SEAL RETAINER
26 LOWER OUTER RING (TWO-PIECE FORGED TYPE)
27 BOLT, NUT, AND WASHER
28 UPPER OUTER RING (TWO-PIECE FORGED TYPE)

Figure 57. Rotor Controls (Swashplate).

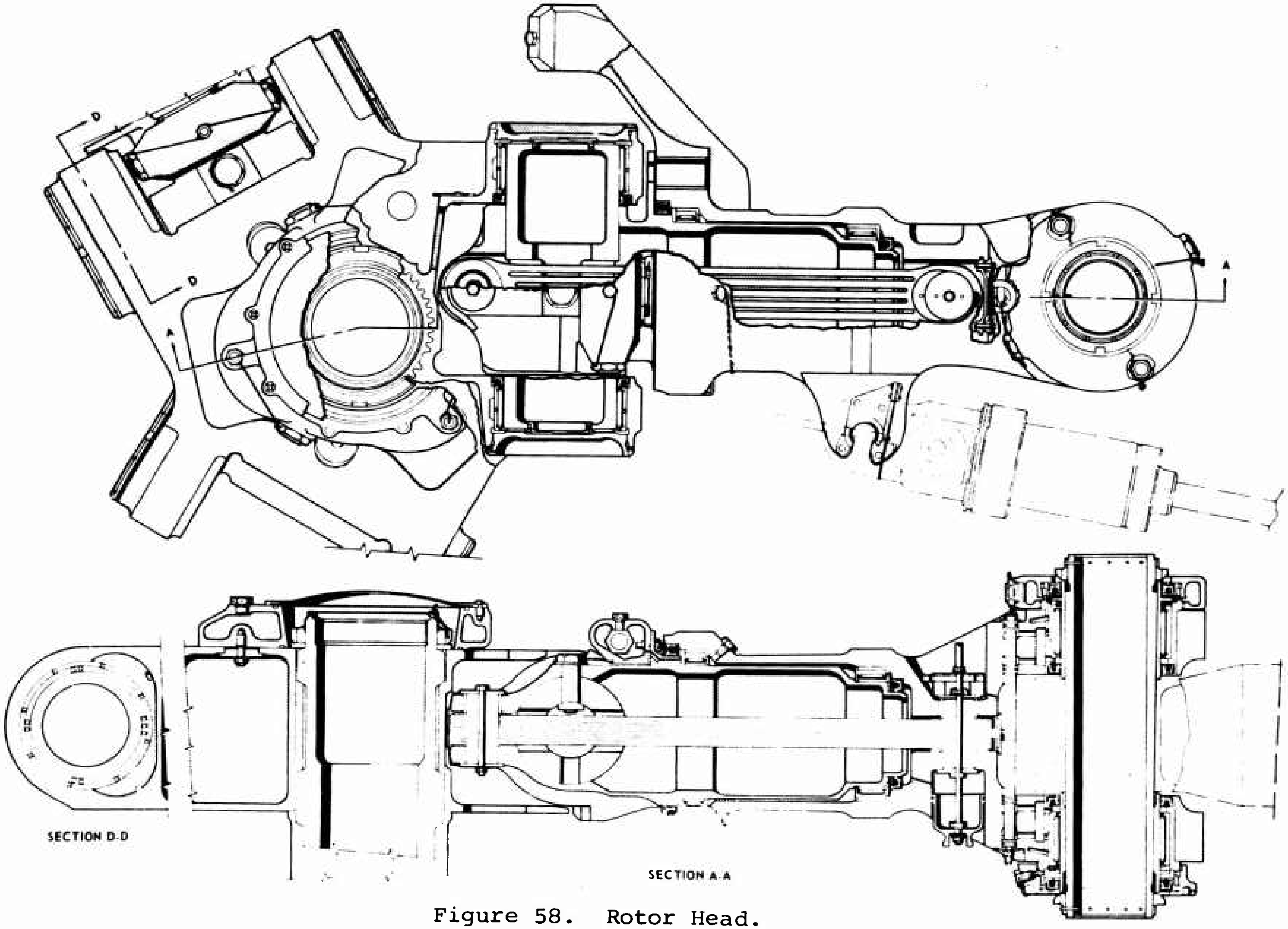


Figure 58. Rotor Head.

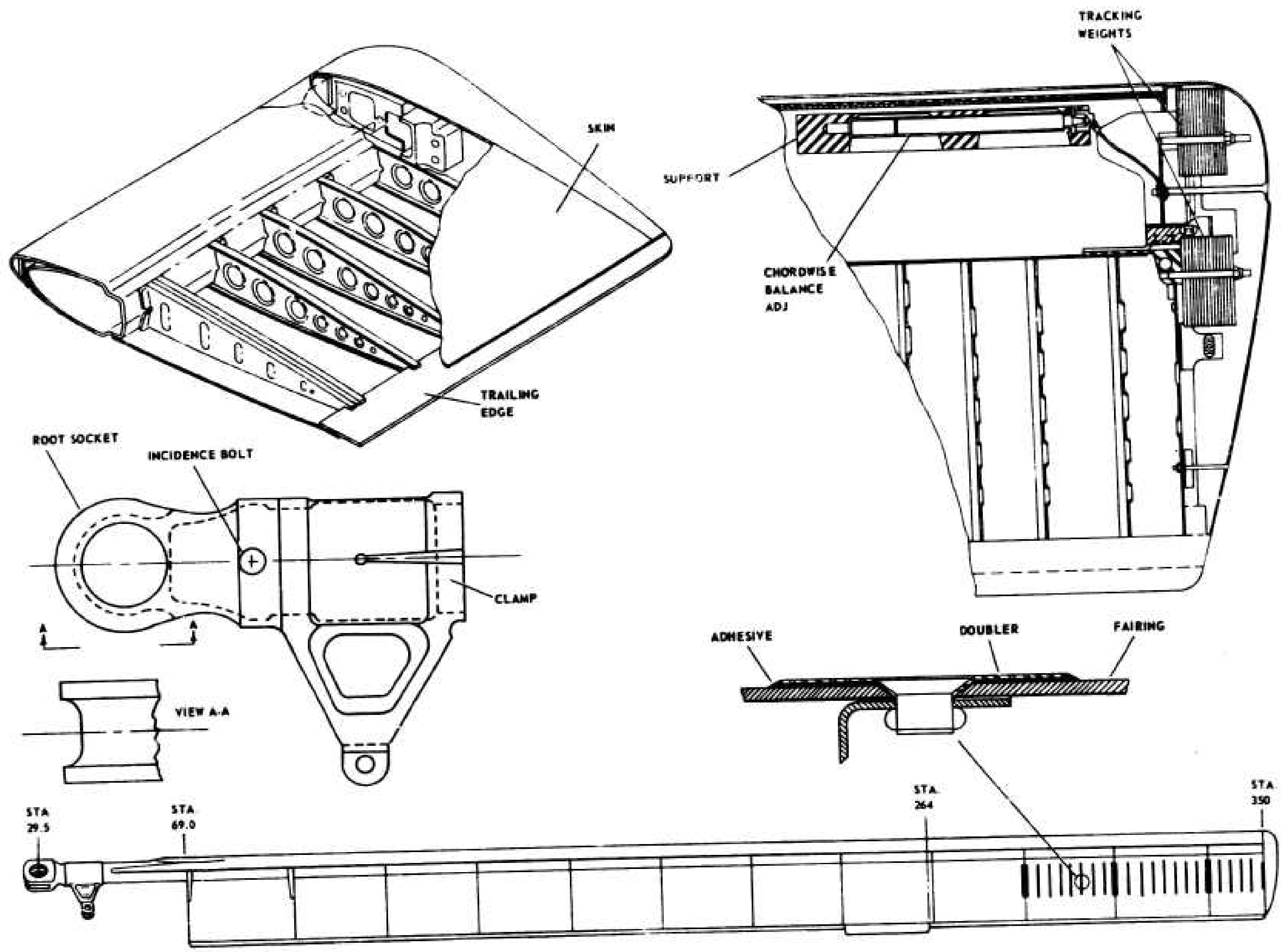


Figure 59. Rotor Blade.

APPENDIX II

COMPARISON OF FIELD AND TEST DETECTION OF CH-47 RELIABILITY PROBLEMS

This appendix contains the detailed data of failure modes and test detection on the CH-47. This data was used for two main purposes: (1) the creation of the off-the-board MTBR for Helicopters "A" and "B", and (2) the determination of test techniques' effectiveness in detecting problems.

Each assembly of the CH-47's major dynamic system was reviewed and is listed separately. Eight assemblies were considered:

1. Forward transmission (Table XIX)
2. Aft transmission (Table XX)
3. Combining transmission (Table XXI)
4. Engine transmission (Table XXII)
5. Drive shafting (Table XXIII)
6. Rotor controls (Table XXIV)
7. Rotor head (Table XXV)
8. Rotor blades (Table XXVI)

For each failure mode listed, a test detection evaluation is shown for those test techniques that were actually used, or for those that could have been used, on the CH-47.

The test detection identification symbols for each problem and test technique are as follows:

- ● Problem was actually detected
- ⊕ Problem could have been detected except for the presence of artificial restraints
- O Problem could have been detected if test had been operated for sufficient duration
- X Problem cannot be detected because of inherent restraints

Summaries of the detection histories and potential for each component are provided in Tables III through XII.

TABLE XIX. FIELD AND TEST DETECTION COMPARISON OF RELIABILITY PROBLEMS FOR FORWARD TRANSMISSION

Test Key:
● Detected problem.
O Can detect with adequate test duration.
⊕ Can detect if artificial restraints are eliminated. Duration was adequate.
x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic System Test			Inherent Restraints
1	Wear on pinion gear support thrust flange (114D1045) creating input pinion axial play	Field (Unscheduled removal)	Rotation of thrust bearing outer race and/or alternating thrust loads due to reverse loading (autorotation)	1,000	x	x	O	O	O	O			Time limit	Closed loop or tiedown cannot reverse under adequate controls	O	O			Load application
2	Wear of pinion gear spacers faces causing contamination and/or axial play	Field (Unscheduled removal)	Rotation of spacers on shaft.	1,000	●	●	O	O	O	O			Time limit		O	O			Load application
3	Wear of pinion gear lubricators causing contamination 114D1074	Field (Unscheduled removal)	Wear of thrust shoulder (see problem No. 1) due to bearing outer race axial or radial movement	1,000	x	x	O	O	O	O			Time limit	See problem No. 1	O	O			Load application
4	Pinion locknut backing off and gouging of housing (nylon insert type) (See problem No. 11)	Field (Unscheduled removal)		3,000	O	O	●	O	O	O			Time limit		O	O			Load application
5	Mounting lug for pivoting actuator cracked	Field (Safety)	Fatigue failure from fretted bolt hole.	100,000	x	O	O	O	O	O			Time limit	Closed loop does not have actuator mounted on lug	O	O			Load application
6	114D1043 sun gear tooth cracked	Field (Safety)		1,000	●	●	O	O	O	O			Time limit		O	O			Load application

TABLE XIX - Continued

Test Key: ● Detected problem. O Can detect with adequate test duration. ⊕ Can detect if artificial restraints are eliminated. Duration was adequate. × Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic System Test			Inherent Restraints
7	Planet bearing retainers (114D2074) cracked first stage	Field (Unscheduled removal)		3,000	O	O	●	O	O	O			Time limit		O	O			Load application
8	Pump and filter mounting studs stripped. Filter falls from transmission or leaks	Field (Unscheduled removal)	Maintenance damage. Studs overtorqued during unanticipated frequent filter removals	10,000	⊕	⊕	●	⊕	⊕	⊕			Maintenance personnel and techniques for removal and replacement		O	O			
9	First stage planet bearing cage failures (114DS244)	Field (Unscheduled removal)		100	●	●	●	●	●	⊕			New design in later configuration		O	O			Loads
10	Rotor shaft thrust bearing spalling (114DS144)	Field (Safety)		10,000	O	O	O	O	O	O			Time limit		O	O			
11	Tangs of lockwasher (114D - 1109) broken/ worn (new positive retention locknut design)	Field (Unscheduled removal)	Material from vendor not per specification	10,000	O	O	O	O	O	O			Time limit		O	O			
12	First stage retaining bolt (114D1106) failed in threaded area (See problem No. 23)	Field (Unscheduled removal)	Fatigue - poor thread design	100,000	O	O	O	O	O	O			Time limit		O	O			Loads

TABLE XIX - Continued

Test Key:
- ● Detected problem.
- O Can detect with adequate test duration.
- ◉ Can detect if artificial restraints are eliminated. Duration was adequate.
- x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic System Test			Inherent Restraints
13	Thrust bearing retainer (114-D1049) cracked	Test (Safety)	Inadequate strength for reverse loads	100,000	x	x	O	x	O	O			Time limit	Realistic reverse loads can not be applied in bench and tiedown and Eglin	x	x			Loads
14	Thrust bearing retainer (114D-1049) wear steps	Field (Maintenance)	Rotation of thrust bearing outer race and/ or reverse loads	5,000	x	x	O	x	O	O			Time limit	Realistic reverse loads can not be applied in bench, tiedown and Eglin	x	x			Loads
15	Internal portion of Mag plug (B-720) disengages from body	Field (Unscheduled removal)	Insufficient edge crimping distance	30,000	O	O	O	O	O	O			Time limit		O	O			
16	Bearing housing liners worn	Field (Maintenance)	Bearing outer race rotation	1,000	●	●	O	O	O	O			Test acceptance criteria for bench time limit		O	O			Loads
17	Filler cap (F900) leaks, loose rivets and excessive play	Field (Maintenance)	Insufficient strength and transmission vibration	1,000	●	●	O	O	O	O			Time limit		O	O			
18	Second stage planet bearing (114DS258) incipient spalling on inner race	Field (Unscheduled removal)		500	●	●	O	O	O	O			Time limit		O	O			Loads

TABLE XIX - Continued

Test Key:
● Detected problem.
O Can detect with adequate test duration.
⊕ Can detect if artificial restraints are eliminated. Duration was adequate.
x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic System Test			Inherent Restraints
19	Oil pressure fluctuation	Field (Unscheduled removal)	Incompatible relief valve spring tension	500	⊕	⊕	●	⊕	⊕	⊕			Manufacturing variations in spring/pump		O	O			
20	Lockwasher (114-D2158) tangs disengaged from nut or broken	Field (Unscheduled removal)	Assemble error	50,000	●	O	O	O	O	O			Time limit		O	O			
21	Rust inside hollow stemmed mounting bolts 114D2162	Field (Maintenance)	Inadequate corrosion protection against water	10,000	x	O	O	O	O	O			Time limit	Environment, lack of moisture	x	O			Environment
22	Fatigue failure of spiral bevel gear tooth	Test	Resonant condition at operating RPM	100	●	⊕	⊕	⊕	⊕	⊕			Later tests had spiralox ring fix		O	O			
23	First stage retaining bolt (AN4-25A) failed (See problem No. 12)	Test (Unscheduled removal)	Fatigue	3,000	O	O	●	O	O	O			Time limit		O	O			Load application
24	Spalling of 114DS250 first stage support bearing	Field (Unscheduled removal)		1,000	⊕	●	O	O	O	O			Low time on individual specimens. Time limit for other tests		O	O			Load
25	VS10304-7 locknut backed off	Test (Safety)	Insufficient nylon crimp	500	●	⊕	⊕	⊕	⊕	●			Later tests had improved quality control on crimp		O	O			

TABLE XIX - Continued

Test Key:
● Detected problem.
O Can detect with adequate test duration.
◐ Can detect if artificial restraints are eliminated. Duration was adequate.
x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic System Test			Inherent Restraints
26	114DS161 rotor thrust bearing scuffed and scored balls	Test (Safety)	Rough races	100	●	◐	◐	◐	◐	◐			Later tests had improved configuration		0	0			Loads
27	Oil sloshing out of filler pipe	Test (Unscheduled removal)	Oil sloshing in transmission	100	◐	◐	●	◐	◐	◐			Oil leakage not recorded during bench and tiedown. Later tests had improved configuration		0	0			
28	114D2077-1 second stage sun gear tooth spalls/pitting	Field (Unscheduled removal)		500	●	◐	0	0	0	0			Later test had improved configuration Time limit		0	0			Loads
29	114D1053-1 ring gear spalled	Field (Unscheduled removal)	Nonmetallic inclusion in material resulted in sub-surface fatigue	500	●	◐	◐	◐	◐	◐			Later tests had vacuum melt steel		0	0			Loads
30	114D2076 first stage planet gear spall	Test (Unscheduled removal)	Fatigue	500	●	◐	◐	◐	◐	◐			Later tests had vacuum melt steel		0	0			Loads
31	114D1084 plug backed out	Test (Unscheduled removal)	Plug undersize from excess of installations	1,000	●	●	◐	◐	●	◐			Later tests had modified installation		0	0			
32	114S240 pinion bearing spalled	Field (Unscheduled removal)		50,000	●	0	0	0	0	0			Time limit		0	0			Loads
33	114DS244-13 planet assembly spalled	Field (Unscheduled removal)		500	●	●	0	0	0	0			Time limit		0	0			Loads

TABLE XIX - Continued																			
Problem					Existing Test Techniques and Detection Potential								Test Key: ● Detected problem. O Can detect with adequate test duration. ⊕ Can detect if artificial restraints are eliminated. Duration was adequate. × Cannot detect - due to inherent restraints.		New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic System Test			Inherent Restraints
34	114D1089-9 lower housing cracked mounting flange	Test (Unscheduled removal)	Handling damage	10,000	●	⊕	⊕	⊕	⊕	⊕			Maintenance procedures are not common to all test techniques		O	O			
35	114DS262-1 pinion bearing wear on end faces and inner diameter fretting	Field (Unscheduled removal)	Inner race rotation	500	●	⊕	⊕	⊕	⊕	⊕			Later tests had increased press fit		O	O			Load
36	114DS145 rotor radial bearing outer race rotation	Field (Unscheduled removal)		10,000	O	O	●	O	O	O			Time limit		O	O			Load
37	114DS243 first stage sun bearing outer race rotation	Field (Maintenance)		5,000	O	O	O	O	O	O			Time limit		O	O			Load
38	114D2184 first stage planet bearing retainer cracked and broken flanges	Field (Maintenance)		3,000	O	O	O	O	O	O			Time limit		O	O			Load
39	Oil starvation of forward transmission thrust bearing	Test (Unscheduled removal)	Jet not drilled during manufacturing	100	●	⊕	⊕	⊕	⊕	⊕			Manufacturing process modified on later tests		O	O			

TABLE XIX - Continued

Test Key:
- ● Detected problem.
- O Can detect with adequate test duration.
- ⊕ Can detect if artificial restraints are eliminated. Duration was adequate.
- x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic System Test			Inherent Restraints
40	Filler mounting stud pullout	Test (Unscheduled removal)		10,000	⊕	●	⊕	⊕	⊕	⊕			Maintenance procedure not similar on all tests		O	O			
41	114D1044 spiral bevel pinion gear scuffed teeth	Field (Unscheduled removal)	Higher loads on CH-47C	500	O	●	⊕	⊕	⊕	⊕			Time limitation on bench. Configuration modified on other test		O	O			Loads
42	114D1243 first stage sun gear spalled and scuffed teeth	Test (Unscheduled removal)	Higher loads on CH-47C	500	O	●	⊕	⊕	⊕	⊕			Time limitation on bench. Configuration modified on other test		O	O			Loads
43	114D2251 first stage planet scuffed teeth	Test (Unscheduled removal)	Higher loads on CH-47C	500	O	●	⊕	⊕	⊕	⊕			Time limitation on bench		O	O			Loads
44	114DS149 input seal leakage	Test (Unscheduled removal)		5,000	O	●	O	O	O	O			Time limit		O	O			
45	114DS281 planet bearing - Flaking outboard edge inner race	Test (Unscheduled removal)	Manufacturing error. Geometrical error in bearing	500	⊕	●	⊕	⊕	⊕	⊕			All other tests had bearing per drawing		O	O			Loads

TABLE XX. FIELD AND TEST DETECTION COMPARISON OF RELIABILITY PROBLEMS FOR AFT TRANSMISSION

Test Key:
- ● Detected problem.
- ○ Can detect with adequate test duration.
- ⊕ Can detect if artificial restraints are eliminated. Duration was adequate.
- x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic System Test			Inherent Restraints
1	First stage planet gear roller bearing (114DS244) cage failures	Field (Unscheduled removal)		500	○	●	○	○	○	○			Time limit		○	○			Load
2	Second stage planet bearing (114DS258) spalled on inner race	Field (Unscheduled removal)		500	●	●	⊕	⊕	●	⊕			Later tests had improved design		○	○			Load
3	Pinion locknut (VS10304-12) backing off	Field (Unscheduled removal)		3,000	○	○	○	○	○	○			Time limit		○	○			Load
4	Quill shaft (114D2105) shearing or twisted due to clutch slippage	Field (Safety)	Instantaneous matching of auxiliary gear-box and rotor speed during APU shutdown and pull	10,000	x	⊕	○	○	○	○			Tiedown procedure did not require APU shutdown during RPM drop. Time limit	Bench, closed loop cannot drop RPM rapidly	○	○			Load
5	Second stage carrier bearing (114DS25402) spalled on outer race.	Field (Unscheduled removal)		1,000	●	●	⊕	⊕	⊕	⊕			Later test had M-50 bearings		○	○			Load
6	Fluctuating oil pressure	Field/ (Maintenance)	Oil vortexing in sump and incompatible pump relief valve.	100	●	⊕	○	⊕	⊕	⊕			Bench tests had non-production		○	○			
7	First stage planet bearing retainers (114D2074) cracked.	Field (Unscheduled removal)	Fatigue	500	●	⊕	●	○	○	○			Tiedown had low time samples. Time limit		○	○			Load

TABLE XX - Continued

Test Key:
- ● Detected problem.
- O Can detect with adequate test duration.
- ◉ Can detect if artificial restraints are eliminated. Duration was adequate.
- x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic System Test			Inherent Restraints
8	Filter cap (F900B) leaking excessive play, loose rivets.	Field (Mainten- ance)	Vibration levels excessive for design.	3,000	●	●	O	O	O	O			Tiedown had a modified configura- tion. Time limit		O	O			
9	Second stage planet bearing retainer (114D- 2082-4) cracked.	Field (Unscheduled removal)		1,000	●	●	O	O	O	O			Time limit		O	O			Loads
10	Tang on lock- washer (114D2158- 3) disengaged from nut on carrier support.	Field (Mainten- ance)	Manufacturing error, tang deformed during assembly	50,000	●	O	O	O	O	O			Time limit		O	O			
11	First stage planet gear support (114D212- 3) heavy wear on large flang- ed end.	Field (Unscheduled removal)	Loss of nut torque and ro- tation of support.	3,000	O	●	O	O	O	O			Time limit		O	O			Loads
12	First stage planet gear support	Field (Unscheduled removal)		500	●	●	◉	●	●	●			New config- uration on subsequent tests		O	O			Loads
13	Spiral bevel pinion spacers (114D2127-3 and 114D2146-2) scoring on bores and faces	Field (Mainten- ance)	Rotation of spacers on shaft.	1,000	●	●	O	O	O	O			Tiedown had low time samples. Time limit		O	O			Loads

TABLE XX - Continued

Test Key: ● Detected problem. O Can detect with adequate test duration. ◉ Can detect if artificial restraints are eliminated. Duration was adequate. x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic System Test			Inherent Restraints
14	Sprag clutch (114DS246-1) slippage and wear of sprags	Field (Unscheduled removal)		500	●	●	O	O	O	O			AGB did not overrun clutch for adequate time in bench. Time limit		O	O			
15	Liners (114D-2048 and 114D-2088) worn or scored	Field (Mainten-ance)	Bearing outer race rotation	1,000	●	●	O	O	O	O			Inadequate test accept criteria Time limit		O	O			Loads
16	Housing (114D-2167) cracked at oil passage	Field (Safety)		10,000	O	O	O	O	O	O			Time limit		O	O			
17	Quill shaft (114D2105) splines worn at both ends	Field (Unscheduled removal)		[illegible],000	O	O	O	O	O	O			Time limit		O	O			Loads
18	Aft vertical shaft seal (114DS267-3) leakage	Field (Unscheduled removal)	Maintenance dam-age during instal-lation of aft vertical shaft	1,000	◉	●	●	O	O	O			Time limit		O	O			
19	First stage carrier bearing (114DS250-1) spalled	Field (Unscheduled removal)		1,000	●	◉	O	O	O	O			Inadequate time on individual samples on tiedown. Time limit		O	O			Loads
20	Ingestion of flight control pump and utility pump quill shaft into aux-iliary gearbox	Field (Unscheduled removal)	Pump shaft re-tainer failure with lack of plug in drive gear	50,000	O	O	O	O	O	O			Time limit		O	O			

TABLE XX - Continued

Test Key: ● Detected problem. O Can detect with adequate test duration. ◐ Can detect if artificial restraints are eliminated. Duration was adequate. x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic System Test			Inherent Restraints
21	Sun gear bearing (114DS243-1) broken roller with spalling on longitudinal line	Test (Unscheduled removal)	Material defect	500	●	●	●	●	●	●			Later tests has improved quality		O	O			Loads
22	Spiral bevel pinion gear bearing (114DS-262) inner race rotation and wear	Field (Unscheduled removal)	Insufficient press fit on shaft	500	●	●	●	●	●	●			Later tests had increased press fit inner race		O	O			Loads
23	Second stage carrier support bearing (114DS-250) scored on outer diameter	Test (Maintenance)	Outer race rotation due to loose locknut, manufacturing error	50,000	●	●	●	●	●	●			Later tests did not have loose locknuts		O	O			Loads
24	First stage sun gear (114D2066) spalled	Field (Unscheduled removal)		1,000	●	●	●	●	●	●			Later tests had improved configuration. Time limit		O	O			Loads
25	Second stage sun gear (114D2077) scuffing and pitting of teeth at pitch lines	Field (Unscheduled removal)	Scuffing from excessively full tooth involute profile	500	●	●	O	O	O	O			Time limit		O	O			Loads
26	Lower sun gear support housing (114D2167) cracked on lower housing mounting flange	Test (Unscheduled removal)	Handling damage	10,000	●	●	●	●	●	●			Maintenance procedure not common to all tests		O	O			

TABLE XX - Continued

Test Key:
- ● Detected problem.
- ○ Can detect with adequate test duration.
- ⊕ Can detect if artificial restraints are eliminated. Duration was adequate.
- × Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic System Test			Inherent Restraints
27	Upper housing (114D2166) crack originating at flash in support radius	Test (Unscheduled removal)	Sharp radius	100,000	●	●	○	○	○	○			Time limit		○	○			
28	Retainer (114D-2089) worn excessively on surface which meets 114DS254 bearing	Field (Unscheduled removal	Rotation of bearing outer race	500	●	●	○	○	○	○			Time limit		○	○			Loads
29	Planet assembly (114DS281) spalled gear tooth	Test (Unscheduled removal)	Bearing not manufactured to drawing tolerance. Manufacturing error	1,000	●	●	●	⊕	⊕	⊕			Later tests had improved quality control		○	○			Loads
30	Upper cover (114D2166) cracked in corner of bolt hole spot face	Test (Unscheduled removal)	Due to misinterpretation of blueprint by vendor, fatigue crack initiated in very sharp corner radius	10,000	●	⊕	⊕	⊕	⊕	⊕			Later tests had improved quality control		○	○			Loads
31	Locknut (114D2072) loose	Test (Unscheduled removal)	Manufacturing error	50,000	●	⊕	⊕	⊕	⊕	⊕			Later tests had improved quality control		○	○			Loads
32	Spiral bevel ring gear (114D2062) fatigue crack progressed from a bolt hole in ring gear flange through tooth portion	Test (Safety)	Heavy fretting corrosion on flange and at fatigue origin	100,000	●	○	○	○	○	○			Time limit		○	○			Loads

TABLE XX - Continued

Test Key:
● Detected problem.
○ Can detect with adequate test duration.
⊕ Can detect if artificial restraints are eliminated. Duration was adequate.
× Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic System Test			Inherent Restraints
33	Second stage planet gear (114D2084) slight scuffing and pitting on several teeth	Test (Unscheduled removal)	Scuffing and high contact pressures most probably due to excessively full tooth involute profile	100	●	⊕	⊕	⊕	⊕	⊕			Profile modified on subsequent tests		○	○			Loads
34	Spiral bevel pinion gear (114D2045) spalls on drive side flanks	Test (Unscheduled removal)	Heavy contact and interference	100	●	⊕	⊕	⊕	⊕	⊕			Profile modified on subsequent tests		○	○			Loads
35	Spiral bevel ring gear (114D2062) spalling on tips of teeth	Teeth (Unscheduled removal)	Heavy contact	100	●	●	⊕	⊕	⊕	⊕			Profile modified on subsequent tests		○	○			Loads
36	Oil leakage from sight gage	Field (Mainten-ance)		5,000	⊕	●	○	●	●	○			Bench lacks acceptable criteria. Flight air-craft time limit		○	○			
37	Pump drive gear (114D2132) scor-ing on outer diameter of shaft	Field (Mainten-ance)		100,000	○	●	○	○	○	○			Time limit		○	○			
38	Sprag clutch (114DS246) broken drag strip	Field (Unscheduled removal)		5,000	○	○	○	○	○	○			Time limit		○	○			Loads

TABLE XX - Continued

Test Key:
● Detected problem.
O Can detect with adequate test duration.
⊕ Can detect if artificial restraints are eliminated. Duration was adequate.
× Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic System Test			Inherent Restraints
39	Fan drive bearing (114DS253) scored, fretted, corroded; inner race gouged	Field (Maintenance)		5,000	O	O	O	O	O	O			Time limit		O	O			Loads
40	Access. drive pinion shaft bearing (114DS247) - scored on roller surface	Field (Unscheduled removal)		100,000	O	●	O	O	O	O			Time limit		O	O			
41	Second stage planet sun gear (114D2077) spalled on drive side	Field (Unscheduled removal)		500	O	●	⊕	⊕	⊕	⊕			Time on bench. Later design on subsequent tests		O	O			Loads
42	Pinion gear bearing retainer (114D2147) fretted and worn	Field (Unscheduled removal)		50,000	O	●	O	O	O	O			Time limit		O	O			Loads
43	Sun gear bearing (114DS242) spalled on inner diameter of outer race	Field (Unscheduled removal)		100,000	O	●	O	O	O	O			Time limit		O	O			
44	Quill shaft (114D2105) - Magnaflux indication at root of spline tooth	Test (Unscheduled removal)		10,000	⊕	●	⊕	⊕	⊕	⊕			Improved quality control on subsequent tests		O	O			

TABLE XX - Continued

	Problem				Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
					Test Key: ● Detected problem. O Can detect with adequate test duration. ⊕ Can detect if artificial restraints are eliminated. Duration was adequate. x Cannot detect - due to inherent restraints.														
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic System Test			Inherent Restraints
45	Oil seal retainer (114D2089) cracked	Field (Unscheduled removal)		500	O	●	O	O	O	O			Time limit		O	O			Loads
46	Retainer (114D2133) worn	Test (Maintenance)		100,000	O	●	O	O	O	O			Time limit		O	O			
47	Quill shaft (114D2116) - Magnaflux indications adjacent to retaining pin hole	Test (Unscheduled removal)		10,000	O	●	O	O	O	O			Time limit		O	O			
48	Accessory gear (114D2108) - Magnaflux indications in web	Test (Unscheduled removal)	Straightening process	100,000	O	●	O	O	O	O			Time limit		O	O			
49	Filter oil bypass button popped with no contamination	Test (Maintenance)	Due to cold temperatures	100	x	x	x	●	x	⊕				Lack of adequate cold temperature in bench and flight. Alaska had improved configuration.	x	x			Environment not practical for open loop and dynamic systems
50	114D2184 first stage planet bearing retainer cracked and broken flanges	Field (Maintenance)		3,000	O	O	O	O	O	O			Time limit		O	O			Loads

TABLE XXI. FIELD AND TEST DETECTION COMPARISON OF RELIABILITY PROBLEMS FOR COMBINING TRANSMISSION

Test Key:
- ● Detected problem.
- O Can detect with adequate test duration.
- ⊕ Can detect if artificial restraints are eliminated. Duration was adequate.
- x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic Systems			Inherent Restraints
1	Wear on input pinion assembly thrust retainer 114D5046 causing axial play	Field (Unscheduled removal)	Rotatio of outer race of bearing 114DS642	3,000	O	O	O	O	O	O			Time limit		O	O			Loads
2	Input pinion locknut backs off causing contamination	Field (Unscheduled removal)		3,000	O	O	O	O	O	O			Time limit		O	O			Loads
3	Input pinion roller bearing spalling and wear on inner race (114DS542)	Field (Unscheduled removal)		1,000	●	●	O	O	O	O			Time limit		O	O			Loads
4	Pinion spacer wear on bores and faces (114D5071 and 114D5051)	Field (Unscheduled removal)	Rotation of spacers on shaft	3,000	●	O	O	O	O	O			Time limit		O	O			Loads
5	Spalled ball on input gear bearing (114DS541)	Field (Unscheduled removal)		100,000	●	O	O	O	O	O			Time limit		O	O			
6	Wear on bearing liners	Field (Maintenance)	Bearing outer race rotation	1,000	O	●	O	O	O	O			Time limit		O	O			Loads
7	Wear, nicks, on pin and top of filler neck	Field (Maintenance)		3,000	⊕	●	●	O	O	O			Bench acceptance criteria. Rest are time limit		O	O			
8	Relief valve piston shaft galling - valve seat wear	Field (Maintenance)	Inadequate shaft support	500	⊕	⊕	⊕	●	⊕	⊕			Acceptance criteria on all tests		O	O			

TABLE XXI - Continued

Key: ● Detected problem. ○ Can detect with adequate test duration. ◐ Can detect if artificial restraints are eliminated. Duration was adequate. × Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic Systems			Inherent Restraints
9	Reservoir cover leakage	Field (Maintenance)	Maintenance personnel stepped on cover coupled with manufacturing tolerances	10,000	◐	◐	◐	◐	◐	◐			Test maintenance procedures on all tests. Acceptance criteria on bench		○	○			
10	Sight glass bulging and cracks (114DS106)	Field (Maintenance)		3,000	◐	●	●	○	○	○			Acceptance criteria on bench and time on subsequent tests		○	○			
11	Filter mounting stud stripped	Field (Unscheduled removal)		100,000	◐	◐	◐	◐	◐	◐			Maintenance frequency and procedure on all tests		○	○			
12	Oil drains out of reservoir when filter is inspected	Field (Maintenance)		100	●	◐	◐	◐	●	◐			Acceptance criteria		○	○			
13	Aircraft started with dephasing mechanism disengaged	Field (Safety)		10,000	◐	◐	●	◐	◐	◐			Operation of mechanism not used during other tests		○	○			
14	Pump quill shaft disengaged	Field (Unscheduled removal)	Snap ring deformed during assembly of pump onto transmission	10,000	◐	◐	●	◐	◐	◐			Configuration modification. Time limit		○	○			
15	Spalling on inner race (114DS543)	Field (Unscheduled removal)	Fatigue	3,000	●	◐	◐	◐	◐	◐			Configuration modification. Time limit		○	○			Loads

TABLE XXI - Continued

Test Key: ● Detected problem. O Can detect with adequate test duration. ⊕ Can detect if artificial restraints are eliminated. Duration was adequate. x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic Systems			Inherent Restraints
16	Housing assembly has cracked web at junction of oil pump mounting pad and output pinion mounting pad (114D5040)	Field	Thin web	3,000	⊕	●	⊕	⊕	⊕	⊕			Configuration different on other tests. Time limit		O	O			Loads
17	Spiral bevel ring gear has several failed teeth (114D5056-1)	Field (Safety)	Due to fatigue originating at a spall on flank of a tooth.	100,000	●	O	O	O	O	O			Time limit		O	O			
18	(114DS572) aft output shaft bearing loaded half of split inner race spalled over 360 degree path, balls spalled, dented, scratched, pitted.	Field (Unscheduled removal)	Possibly due to marginal lubrication to inner thrust race	100,000	●	O	O	O	O	O			Time limit		O	O			
19	Evidence of rotation of bearings 114DS252 114DS549 114DS542 114DS543 114DS545 114DS548	Field (Unscheduled removal)		3,000	⊕	●	O	O	O	O			Test acceptance criteria bench. Time limit		O	O			Loads

TABLE XXI - Continued

Test Key:
● Detected problem.
O Can detect with adequate test duration.
⊕ Can detect if artificial restraints are eliminated. Duration was adequate.
x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop Bench Endur.	Dynamic Systems			Inherent Restraints
20	Scoring on rollers of input shaft bearing (114DS642)	Field (Unscheduled removal)		50,000	O	●	O	O	O	O			Time limit		O	O			
21	Spline area of spiral bevel ring gear fretting (114D5056)	Field (Maintenance)		1,000	O	●	O	O	O	O			Time limit		O	O			Loads
22	Spline area of output shaft fretted (114D5068)	Field (Maintenance)		1,000	O	●	O	O	O	O			Time limit		O	O			Loads
23	Scuffing of spiral bevel ring gear (114D5244) and pinion gear (114DS245)	Test (Maintenance)	Edge at top of gear teeth not properly broken per blueprint	100	⊕	●	⊕	⊕	⊕	⊕			Configuration different on other test		O	O			Loads
24	Housing assembly has 3/8 inch crack at internal rib support of 114DS576 bearing (114DS240)	Test (Unscheduled removal)	Crack caused by fatigue and casting defect. Microporosity present in area contributed to the problem	500	⊕	●	⊕	⊕	⊕	⊕			Configuration not present		O	O			Loads
25	Adapter bushing loose in housing causing severe oil leak (114D5243)	Test (Unscheduled removal)	Overtorquing an "AN" fitting into bushing which sheared roll pins that secure bushing to transmission	100	⊕	●	⊕	⊕	⊕	⊕			Maintenance procedures not present (roll pin diameter increased)		O	O			
26	Light skidding and smearing on inner race of thrust bearing (114DS541)	Test (Unscheduled removal)		100,000	O	●	O	O	O	O			Time limit		O	O			

TABLE XXII. FIELD AND TEST DETECTION COMPARISON OF RELIABILITY PROBLEMS FOR ENGINE TRANSMISSION

Test Key:
- ● Detected problem.
- ○ Can detect with adequate test duration.
- ◐ Can detect if artificial restraints are eliminated. Duration was adequate.
- × Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop	Dynamic Systems			Inherent Restraints
1	Cage failures of output shaft roller bearing 114DS645-2	Field (Unscheduled removal)		500	○	●	○	○	○	○			Time limit		○	○			Loads
2	Inner race cracks/ball spalling input roller bearings (114DS640 and 114DS650)	Field (Unscheduled removal)	Roller skidding on low load conditions	5,000	◐	◐	○	○	○	○			Bench and tiedown not operating at low loads. Subsequent tests. Time limited		○	○			
3	Wear on outer diameter of outer shaft bearing (114DS-645) and wear on assembly liner	Field (Mainten-ance)	Bearing outer race rotation	500	●	●	○	○	○	○			Time limit		○	○			Loads
4	Wear on outer diameter of outer race of input shaft bearing (114DS-640 and 114DS-650) and wear on assembly liners	Field (Mainten-ance)	Bearing outer race rotation	1,000	◐	●	○	○	○	○			Acceptance criteria on bench. Time limit on rest of tests		○	○			Loads
5	Fretting and fatigue failure of ring gear to clutch housing shaft spline housing	Test (Unscheduled removal)	Non-concentric pilot diameters	500	●	●	◐	◐	◐	◐			Configuration modified		○	○			

TABLE XXII - Continued

Test Key:
● Detected problem.
○ Can detect with adequate test duration.
⊕ Can detect if artificial restraints are eliminated. Duration was adequate.
× Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop	Dynamic System			Inherent Restraints
6	Fatigue failure of spiral bevel gear	Field (Unscheduled removal)	Resonant condition at operating RPM.	500	●	●	○	○	○	○			Time limit		○	○			
7	Wear on internal splines on input shaft and chipping of quill shaft spline teeth	Field (Unscheduled removal)	Inadequate lubrication, misalignment, soft surface treatment and engine/box dynamics.	500	⊕	⊕	○	○	○	○			Component configuration not representative. Time limit		○	○			Loads
8	Output shaft seal leakage (114DS649)	Field (Unscheduled removal)		30,000	⊕	●	●	○	○	○			Bench acceptance criteria. Time limit		○	○			
9	Overtemperature during operation	Field (Unscheduled removal)	Inadequate oil scavenging by baffles	100	⊕	⊕	●	●	●	●			Configuration on bench and tiedown		○	○			
10	Wear on sprag race and broken clutch clip, strips broken (114DS646)	Field (Unscheduled removal)		500	●	●	○	○	○	○			Time limit		○	○			
11	Input quill shaft locating shoulder broached on splines (See problem No. 13)	Field (Unscheduled removal)	Forward forces acting upon shaft	3,000	⊕	⊕	○	○	○	●			Acceptance criteria on bench and tiedown. Time limit on rest of tests		○	○			Loads
12	New quill shaft locating shoulder containing pinion shaft (See problem No. 11)	Field (Unscheduled removal)	Same as problem No. 11	1,000	●	●	○	○	○	○			Time limit		○	○			Loads

TABLE XXII - Continued

Test Key:
● Detected problem.
○ Can detect with adequate test duration.
⊕ Can detect if artificial restraints are eliminated. Duration was adequate.
x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop	Dynamic Systems			Inherent Restraints
13	Input pinion nylon locknut backing off VS10304-5	Field (Unscheduled removal)		3,000	●	⊕	○	○	○	●			Configuration change on tiedown. Time limit on subsequent tests		○	○			Loads
14	Output shaft nylon locknut backing off (VS10304-3)	Field (Unscheduled removal)		1,000	○	○	○	○	○	○			Time limit		○	○			Loads
15	Tangs of lock-washer for pinion positive retention lock-nut broken (See problem No. 14)	Field (Unscheduled removal)	Manufacturing error, parts shot-peened prior to de-burring	50,000	○	○	○	○	○	○			Time limit		○	○			
16	Input pinion spacer wear on faces (114D6047) causes axial play	Field (Unscheduled removal)	Spinning of spacers on shaft	500	○	●	○	○	○	○			Time limit		○	○			Load
17	Wear on output shaft splines	Field (Unscheduled removal)	Dynamics of engine output drive shaft to box coupling	5,000	x	○	○	○	○	○			Time limit	Closed loop bench does not simulate aircraft loads	○	○			Load
18	Breather threads stripped in housing causing oil leaking at vent breather attachment	Field (Unscheduled removal)	Maintenance damage, over-torque	10,000	⊕	⊕	⊕	⊕	●	⊕			Maintenance procedure not common to all tests		○	○			

TABLE XXII - Continued

Test Key:
● Detected problem.
○ Can detect with adequate test duration.
⊕ Can detect if artificial restraints are eliminated. Duration was adequate.
× Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop	Dynamic Systems			Inherent Restraints
19	Cracked lubrication baffles	Field (Maintenance)		500	⊕	●	○	○	○	○			Configuration on bench time. Limit on subsequent tests		○	○			
20	Oil drains into engine box, upon start-up oil spills out breather	Field (Maintenance)	High location of reservoir, lack of check valves	100	⊕	⊕	●	⊕	⊕	⊕			Configuration of bench stand. Test criteria on tiedown. Configuration on subsequent tests		○	○			
21	Lockpins on quick-disconnect fittings wear and shut lub off	Field (Safety)	Aircraft vibration	500	×	⊕	⊕	⊕	⊕	⊕			All tests did not have adequate test criteria	Bench does not have aircraft vibration.	○	○			Loads
22	Input pinion thrust bearing balls worn and spalled. (114DS641)	Field (Unscheduled removal)		100,000	●	○	○	○	○	○			Time limit		○	○			
23	Clutch shaft bearing cage had a broken roller retaining tang. (114DS249)	Test (Unscheduled removal)	Possible handling damage	100,000	●	○	○	○	○	○			Time limit		○	○			
24	Clutch roller bearing - spalling on rollers and outer diameter of inner race (114DS647)	Field (Unscheduled removal)		100,000	○	●	○	○	○	○			Time limit		○	○			

TABLE XXII - Continued

Test Key: ● Detected problem. ○ Can detect with adequate test duration. ⊕ Can detect if artificial restraints are eliminated. Duration was adequate. × Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Open Loop	Dynamic Systems			Inherent Restraints
25	Outer race rotation of clutch bearing (114DS249)	Field (Maintenance)		100,000	●	●	○	○	○	○			Time limit		○	○			
26	Fretting on face of pinion gear spacer (114D6061)	Test (Maintenance)		100,000	○	●	○	○	○	○			Time limit		○	○			
27	Input gear bearing spalled on rollers (114DS644)	Field (Unscheduled removal)		100,000	●	○	○	○	○	○			Time limit		○	○			
28	Fatigue failures of pinion gear spir-o-lox damping ring (114DS651)	Test	Due to notched end areas	500	●	⊕	⊕	⊕	⊕	⊕			Configuration modified. Smooth ends on subsequent tests		○	○			Loads

TABLE XXIII. FIELD AND TEST DETECTION COMPARISON OF RELIABILITY PROBLEMS FOR DRIVE SHAFTING

Test Key: ● Detected problem. ○ Can detect with adequate test duration. ◐ Can detect if artificial restraints are eliminated. Duration was adequate. × Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Aft Thrust Brg Back-to-Back	Aft Thrust Brg Full Stand	Tiedown	Flight Test	Eglin	Yuma	Alaska	Artificial Restraints	Inherent Restraints	Shafting Rigs Not Aft	Add Shafting to Closed Loop	Open Loop Xmsn Std Shafting	Dynamic Systems	Inherent Restraints
1	Forward synch shaft adapter leg cracking	Field (Safety)	Fatigue originating in fretted bolt hole	50,000	×			×	○	×	○	○	Time limit on all flight type tests	Bench-shafting designed as fixture. Tiedown and Eglin - Aircraft deflection not present	○	○	○	○	
2	Forward synch shaft adapter cracked through key hole slot	Field (Safety)	Fatigue originating from fretted key slot; inadequate clearance	1,000	×			○	○	○	○	○	Time limit	Bench-shafting considered as fixture	○	○	○	○	
3	Forward synch shaft key slot elongated	Field (Unscheduled removal)	Inadequate clearance	3,000	×			○	○	○	○	○	Time limit	Bench-shafting considered as fixture	○	○	○	○	
4	Excessive gaps in Thomas coupling pack between plates	Field (Unscheduled removal)	Maintenance damage on end plates; unknown forces on other plates	1,000	×			●	◐	○	○	○	Maintenance procedure and acceptance criteria Time limit on rest of test.	Bench shafting considered as fixture	○	○	○	○	
5	Scratches and gouges on drive shaft tubes	Field (Unscheduled removal)	Maintenance damage, foreign object damage. Inadequate airframe to shaft clearance under loads	500	×			●	●	○	○	●	Time limit	Bench shafting considered as fixture	○	○	○	○	
6	Cracks in engine drive shaft Thomas coupling pack plates	Field (Unscheduled removal)		5,000	×			●	○	○	○	○	Time limit	Bench shafting considered as fixture	○	○	○	○	

TABLE XXIII - Continued

Test Key: ● Detected problem. O Can detect with adequate test duration. ◉ Can detect if artificial restraints are eliminated. Duration was adequate. x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Aft Thrust Brg Back-to-Back	Aft Thrust Brg Full Stand	Tiedown	Flight Test	Eglin	Yuma	Alaska	Artificial Restraints	Inherent Restraints	Shafting Rigs Not Aft	Add Shafting to Closed Loop	Open Loop Xmsn Std Shafting	Dynamic Systems	Inherent Restraints
7	Engine drive shaft splines worn, causing vibration	Field (Unscheduled removal)		1,000	x			●	O	O	O	O	Time limit	Bench shafting considered as fixture	O	O	O	O	
8	Drive shaft bearing failures	Field (Unscheduled removal)	Misalignment	1,000	x			●	O	O	O	O	Time limit	Bench shafting considered as fixture	O	O	O	O	
9	Retainer shears cotter pin and backs off (114D3206)	Field (Unscheduled removal)		5,000	x			●	●	O	O	O	Modified configuration	Bench shafting considered as fixture	O	O	O	O	
10	Water entrapment in synch shafts - freezing causing inbalance	Field (Maintenance)	No drainage provisions	10,000	x			O	O	O	O	O	Time limit	Bench shafting considered as fixture	O	O	O	O	
11	Rivets sheared on riveted plate to adapter bolts	Field (Unscheduled removal)	Maintenance damage	3,000	x			●	●	●	●	◉	Configuration modified on later tests	Bench shafting considered as fixture	O	O	O	O	
12	Excessive synch and engine shaft vibration	Field (Unscheduled removal)	Inadequate lubrication of splines	1,000	x			x	O	x	O	O	Time limit	Bench shafting considered as fixture. Tiedown does not have aircraft deflections	x	x	x	x	Aircraft deflections
13	Drive shaft mounts (Lord mounts) wear on center sleeve	Field (Maintenance)	Dirt contamination	500	x			O	O	O	O	O	Time limit	Bench shafting considered as fixture	O	O	O	O	

TABLE XXIII - Continued

Test Key:
● Detected problem.
O Can detect with adequate test duration.
◐ Can detect if artificial restraints are eliminated. Duration was adequate.
x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Aft Thrust Brg Back-to-Back	Aft Thrust Brg Full Stand	Tiedown	Flight Test	Eglin	Yuma	Alaska	Artificial Restraints	Inherent Restraints	Shafting Rigs Not Aft	Add Shafting to Closed Loop	Open Loop Xmsn Std Shafting	Dynamic Systems	Inherent Restraints
14	Drive shaft (Lord mounts) spring failures	Field (Maintenance)	Excessive spring deflection; airframe locally resonant at 6/Rev	100	x			x	●	x	O	O	Time limit	Aircraft fuselage detection not duplicated on tiedown. Bench shafting considered as fixture	x	x	x	x	Load-
15	Worn drive shaft mounting bushing (114D3062)	Field (Maintenance)	Manufacturing error, wrong heat treat	500	x			●	●	●	●	●	Configuration	Bench testing considered as fixture	O	O	O	O	
16	Aft vertical shaft thrust bearing spalling	Field (Safety)		3,000	●	●	●	●	O	O	O	O	Time limit			O	O	O	
17	Aft vertical shaft connecting pin retainer sleeve gouges shaft	Field (Unscheduled removal)	Maintenance damage	3,000	●	●	●	●	●	●	●	●	Test acceptance criteria			O	O	O	
18	Aft vertical shaft upper hub nut threads damaged	Field (Unscheduled removal)	Maintenance damage, cross thread	50,000	●	●	●	●	●	●	●	●	Maintenance procedures vary			O	O	O	
19	Aft thrust bearing oil line to filter attached to adjacent stud	Field (Safety)	Maintenance error	10,000	x	x	x	●	●	●	●	●	Maintenance procedures on aircraft test	Configuration (presence of aircraft frame) not similar on any bench test		O	O	O	
20	Aft vertical shaft bearing seal torn and leaking (114DS-347)	Field (Unscheduled removal)		3,000	O	O	O	●	O	O	O	O	Time limit			O	O	O	

TABLE XXIII - Continued

Problem						Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Closed Loop Bench Endur.	Aft Thrust Brg Back-to-Back	Aft Thrust Brg Full Stand	Tiedown	Flight Test	Eglin	Yuma	Alaska	Artificial Restraints	Inherent Restraints	Shafting Rigs Not Aft	Add Shafting to Closed Loop	Open Loop Xmsn Std Shafting	Dynamic Systems	Inherent Restraints
21	Installation of 114D3112 oil slinger upside down	Test (Unscheduled removal)	Maintenance (Assembly error)	100,000	●	●	●	●	●	●	●	●	Maintenance (assembly) personnel vary			O	O	O	
22	Drive shaft Lord mount bushing shoulder cracked	Test (Maintenance)	Flexing of aircraft structure causes clamp up on shoulder	500	x			x	●	x	O	O	Time limit	Bench shafting considered as fixture. Aircraft deflections not on tiedown and Eglin	x	x	x	x	Aircraft deflections
23	Lord mount centering spring slips out of retainer	Test (Maintenance)	Flexing of aircraft	500	x			x	●	x	O	O	Time limit	Bench shafting considered as fixture. Aircraft deflections not on tiedown and Eglin	x	x	x	x	Aircraft deflections
24	Aft vertical bearing retainer cracked (114D-3107)	Test (Safety)	Reverse thrust	1,000	x			x	●	x	O	O	Time limit	Reverse loads can not be applied on bench, tiedown, or Eglin		x	O	x	Reverse [illegible]
25	Balance weights on drive shaft mounting rivets sheared	Test (Unscheduled removal)	Design deficiency	1,000	x			O	●	O	O	O	Time limit	Bench shafting considered as fixture	O	O	O	O	

Test Key:
● Detected problem.
O Can detect with adequate test duration.
● Can detect if artificial restraints are eliminated. Duration was adequate.
x Cannot detect - due to inherent restraints.

TABLE XXIV. FIELD AND TEST DETECTION COMPARISON OF RELIABILITY PROBLEMS FOR ROTOR CONTROLS

Test Key: ● Detected problem. ○ Can detect with adequate test duration. ● Can detect if artificial restraints are eliminated. Duration was adequate. x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Swashplate Bench Endur.	Whirl Test	Tiedown	Flight Test	Eglin	Yuma	Alaska		Artificial Restraints	Inherent Restraints	Dynamic Systems	Open Loop			Inherent Restraints
1	Swashplate oil leakage	Field (Unscheduled removal)		100	●	●	●	●	●	○	○		Time limit		○	○			
2	Swashplate ball to slider sleeve bearings dislodge and distort or wear retainers (114RS311)	Field (Unscheduled removal)	Inadequate bonding of sleeve bearing; dirt contamination (Manufacturing and environment)	500	x	x	●	○	●	○	○		Time limit on flight test in Yuma and Alaska	Environment not present on bench and whirl tower	○	○			
3	Rotation of swashplate ball bearing outer race in housing (114RS307)	Field (Unscheduled removal)	Inadequate bolt preload on outer race by ~~retainer~~	500	●	●	●	●	●	●	●		Assembly procedures not uniform for tests		○	○			
4	Wear of Teflon sleeve bearings in swashplate; ball to slider and ring to ball (114RS311 and 114RS313)	Field (Unscheduled removal)	Rough surface of slider and ball	1,000	●	●	●	○	○	○	○		Test acceptance criteria on whirl tower. Time limit on flight test, Eglin, Yuma, and Alaska						
5	Flaking of swashplate ball (114R3104) and slider (114R3250) electrolized surface (see problem No. 6)	Field (Unscheduled removal)	Quality control	500	●	●	●	●	●	●	●		Configuration modified from electrolized surface to hardcoat		○	○			
6	Wear on swashplate ball (114-R3100) and slider (114R32-50) aluminum hardcoat surface (see problem No. 5)	Field (Unscheduled removal)	Dirt contamination	1,000	x	x	●	○	○	○	○		Time limit on Eglin, flight test, Yuma and Alaska	Environment not present on bench and tower	○	○			

TABLE XXIV - Continued

Test Key:
- ● Detected problem.
- O Can detect with adequate test duration.
- ● Can detect if artificial restraints are eliminated. Duration was adequate.
- x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Swashplate Bench Endur.	Whirl Test	Tiedown	Flight Test	Eglin	Yuma	Alaska		Artificial Restraints	Inherent Restraints	Dynamic Systems	Open Loop			Inherent Restraints
7	Swashplate ball bearing (114RS-307) spalling	Field (Unscheduled removal)		1,000	●	●	●	O	O	O	O		Test acceptance criteria on tie-down. Time limit on flight test, Eglin, Yuma, and Alaska						
8	Static interference between lower drive arm and upper clevis of upper boost actuators	Field (Unscheduled removal)	Contributing factors: no use of upper boost actuator lock-out blocks, hydraulic power off, and aircraft static position	1,000	x	x	●	●	●	●	●		Test acceptance criteria on tie-down, Eglin and Yuma	Bench and whirl configuration	O	x			Configuration
9	Displacement of retainer holding lower drive arm bearing at connection to swashplate	Field (Unscheduled removal)	Contributing factors: no use of upper boost actuator lock-out blocks, hydraulic power off, and aircraft static position	10,000	x	x	●	●	●	●	●		Test acceptance criteria on tie-down, Eglin and Yuma	Bench and whirl configuration	O	x			Configuration
10	Failure of bolt through head and aft swivel actuator to swashplate (NAS1308-54DW)	Field (Safety)	Fatigue, material defect	100,000	O	O	O	O	O	O	O		Time limit		O	O			
11	Scoring in clevis of rotating swashplate pitch link lugs	Field (Unscheduled removal)	Rotation of pitch links	500	●	●	●	●	●	●	●		Test acceptance criteria		O	O			

TABLE XXIV - Continued

Test Key:
● Detected problem.
○ Can detect with adequate test duration.
● Can detect if artificial restraints are eliminated. Duration was adequate.
x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Swashplate Bench Endur.	Whirl Test	Tiedown	Flight Test	Eglin	Yuma	Alaska		Artificial Restraints	Inherent Restraints	Dynamic Systems	Open Loop			Inherent Restraints
12	Cracked or worn bolt connection bushings (114R3116)	Field (Unscheduled removal)	Combination of brittle materials and maintenance handling damage	3,000	○	○	○	○	○	○	●		Time limit		○	○			
13	Drive collar flange cracks (114R3388)	Field (Unscheduled removal)	Rainshield air-loads into drive collar excessive	5,000	x	x	x	○	x	○	●		Time limit on flight test and Yuma	Airloads not present on bench, whirl, tiedown, and Eglin	x	x			Lack of loads from forward velocity
14	Rainshield cracks (114R-6001)	Field (Maintenance)	Manufacturing error: wrong bonding/ply lay-up arrangement	500	x	x	x	●	x	●	●		Configuration not in test	Airloads not present on bench, whirl, tiedown, and Eglin	x	x			Lack of loads due to forward velocity
15	Rainshield deflects and contacts airframe structure (114R6001) (See problem No. 14)	Field (Maintenance)	High forward speed on CH-47C. Deflection due to airloads	100	x	x	x	●	x	●	●		High speed not performed at Yuma and Alaska	Airloads not present on bench, whirl, tiedown, and Eglin	x	x			Airloads not present
16	Pitch link rod end bearing wear (107-R3559-2 bearing and 114R3006 link)	Field (Maintenance)		100	●	●	●	●	○	○	●		Time limit at Eglin and Yuma		○	○			
17	Pitch link boot material deterioration	Field (Maintenance)		1,000	x	x	x	○	x	○	○		Time limit on flight test, Yuma and Alaska	Airloads not present on bench, whirl, tiedown, and Eglin	x	x			Airloads not present
18	Sight gage glass loose or blown out	Field (Unscheduled removal)	Insufficient edge crimping under effects of pressure and temperature	5,000	●	●	●	●	●	●	●		Configuration of test specimens adequately crimped		○	○			

TABLE XXIV - Continued

Test Key: ● Detected problem. ○ Can detect with adequate test duration. ⊕ Can detect if artificial restraints are eliminated. Duration was adequate. x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Swashplate Bench Endur.	Whirl Test	Tiedown	Flight Test	Eglin	Yuma	Alaska		Artificial Restraints	Inherent Restraints	Dynamic Systems	Open Loop			Inherent Restraints
19	Swashplate oil seal raceway separates from mounting flange in oil tank.	Test (Unscheduled removal)	Differential temperature expansion	100	x	x	x	x	○	x	○		Time at Alaska	Lack of extreme temperatures	x	x			Lack of extreme temperatures
20	Cracking of swashplate lower ring assembly (114R3364)	Test (Unscheduled removal)	Tool marks	3,000	●	●	●	○	○	○	○		Whirl and tiedown configuration. Time limit on flight test, Eglin, Yuma and Alaska		○	○			
21	Cage scraping race ball bearing.	Test (Unscheduled removal)	Faulty installation or manufacture	100	●	●	●	●	●	⊕	⊕		Configuration modified		○	○			
22	Rainshield cracked	Test (Maintenance)	Maintenance damage, stepping on rainshield	100	●	●	●	●	⊕	⊕	⊕		Maintenance procedures vary with tests		○	○			
23	Rainshield contacted by upper drive arm	Test (Maintenance)	Rainshield not per drawing	100	●	●	●	⊕	⊕	⊕	⊕		Configuration		○	○			

TABLE XXV. FIELD AND TEST DETECTION COMPARISON OF RELIABILITY PROBLEMS FOR ROTOR HEADS

Test Key:
● Detected problem.
O Can detect with adequate test duration.
⊕ Can detect if artificial restraints are eliminated. Duration was adequate.
x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Bearing Bench Endur.	Whirl Tower	Tiedown	Flight Test	Eglin	Yuma	Alaska	Rotor Head CF Stop Test	Artificial Restraints	Inherent Restraints	Dynamic Systems				Inherent Restraints
1	Interposer supports broken at the 180 degree band of the interposer (114R2078-1)	Field (Maintenance)		500		O	O	O	O	O	O	x	Time limit	Loads from flapping blades	O				
2	Tie bar (114R-2155-1) excessive gap between bar and washer	Field (Unscheduled removal)	Overspeed of rotors	3,000		⊕	⊕	⊕	⊕	⊕	⊕		Test procedure did not require overspeed		O				
3	Tie bar pin (114R2160) fractured	Field (Safety)	Stress corrosion	100,000		x	x	x	x	x	x		Environment		x				Environment
4	Droop stops (114R2063-7) bent and distorted, missing	Field (Unscheduled removal)	Maneuver and taxi blade flapping	1,000		x	x	●	●	O	O	x	Time limit	Inadequate airloads on blades for whirl tower, tiedown and bench	x				Loads
5	114R2199-1 Thrust washer wear and galling	Field (Maintenance)		500	●	●	O	O	O	O	O		Test acceptance criteria		O				
6	Vertical pin lower bearing seal (114R2143) unseating	Field (Unscheduled removal)	Manufacturing tolerance on outer diameter of seal	50,000	⊕	⊕	⊕	●	⊕	⊕	⊕		Configuration on other tests not similar		O				
7	Vertical pin lower bearing seal (114R2143) leakage	Field (Unscheduled removal)		3,000	O	●	O	O	O	O	O		Time limit		O				
8	Pitch housing seal leakage (114R2141 and 114R2142)	Field (Unscheduled removal)	Sand erosion of seal, centrifugal force acts on sand	500		x	●	O	O	O	O		Time limit	Environment not present on whirl tower	x				Environment

TABLE XXV - Continued

Test Key: ● Detected problem. ○ Can detect with adequate test duration. ⊕ Can detect if artificial restraints are eliminated. Duration was adequate. x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Bearing Bench Endur.	Whirl Tower	Tiedown	Flight Test	Eglin	Yuma	Alaska	Rotor Head CF Stop Test	Artificial Restraints	Inherent Restraints	Dynamic Systems				Inherent Restraints
9	Horizontal pin seal leakage (114R2139)	Field (Unscheduled removal)		3,000	●	○	○	○	○	○	○		Time limit		○				
10	114R2130-1 in-board pitch bearing roller pattern in grinding undercuts	Test (Unscheduled removal)	Manufacturing and quality control	100		●	⊕	⊕	⊕	⊕	⊕		Configuration		○				
11	Sight cup (114R2073-3) cracked and broken	Field (Mainten-ance)	Pressure, temp-erature, main-tenance	100		⊕	●	⊕	⊕	⊕	●		Loads not present on whirl tower. Maintenance procedure differs from test to field		○				
12	Vertical pin (114R2173) seiz-ing, scoring around taper pin, corroded, pitted, scratched, fretted	Field (Mainten-ance)		500	●	●	●	●	○	○	○		Time limit		○				
13	Vertical pin (114R2173) cracked	Field (Safety)	Material defect inclusion	100,000	○	○	○	○	○	○	○		Time limit		○				
14	Rotor hub (114R2052) re-taining nut back-ing off	Field (Safety)		100,000		○	○	○	○	○	○		Time limit		○				
15	Limiters (114R2080-2) chafing grooves in lugs of tanks	Field (Mainten-ance)	Aircraft vibra-tion	500		x	⊕	○	○	○	○	x	Tiedown not shut down frequently. Time limit	Lack of air-craft vib-ration	○				

TABLE XXV - Continued

Test Key: ● Detected problem. ○ Can detect with adequate test duration. ◕ Can detect if artificial restraints are eliminated. Duration was adequate. × Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Bearing Bench Endur.	Whirl Tower	Tiedown	Flight Test	Eglin	Yuma	Alaska	Rotor Head CF Stop Test	Artificial Restraints	Inherent Restraints	Dynamic Systems				Inherent Restraints
16	Spring and bolts chafe and wear centrifugal droop stops	Field (Maintenance)	Aircraft vibration	500		×	○	○	○	○	○	×	Time limit	Aircraft vibration loads	○				
17	Spring leaf (114R2109-1) bent and broken	Field (Unscheduled removal)		1,000		●	●	○	○	○	○		Whirl tower did not have procedure to disconnect blades Time limit on flight aircraft		○				
18	Tank assembly corrosion (114R2053)	Field (Maintenance)	Dissimilar metals	10,000	N/A	○	○	○	○	○	○		Time limit		○				
19	Droop stop clevis broken off tank assembly (114R2053)	Field (Maintenance)	Overtorque of mounting bolts, maintenance damage	100		●	●	◕	●	●	◕	◕	Maintenance procedures		○				
20	Pitch housing (114R2067) cracked in the radius of the broached hole	Field (Safety)	Stress corrosion	100,000		○	○	○	○	○	○		Time limit		○				
21	Housing (114R-2067-6) cracked at lock-out pin hole	Field (Safety)	Stress corrosion due to lockout pin bushing on high side of tolerance	100,000	○	○	○	○	○	○	○		Time limit		○				
22	Pitch bearing inner race displaced and damaged seal	Test/UR	Maintenance procedures in assembly	100		●	●	●	◕	●	◕		Maintenance or assembly procedures vary		○				

TABLE XXV - Continued

Test Key:
● Detected problem.
○ Can detect with adequate test duration.
● Can detect if artificial restraints are eliminated. Duration was adequate.
× Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Bench Endur.	Whirl Tower	Tiedown	Flight Test	Eglin	Yuma	Alaska		Artificial Restraints	Inherent Restraints	Dynamic Systems				Inherent Restraints
23	Pitch shaft (114R2088-12) surface cracked	Field (Unscheduled removal)	Operational error: hydraulic pressure applied to controls with locking pins installed	3,000		●	●	●	●	●	●		Tests did not have lock-pins installed (loads)		○				
24	Lower vertical hinge pin roller bearing (114R-2128) spalled	Field (Unscheduled removal)		5,000	●	●	○	○	○	○	○		Time limit		○				
25	Upper vertical hinge pin roller bearing (114R2129) brinelling and spalling; outer diameter of inner race corrosion cracked	Field (Unscheduled removal)		5,000	●	●	○	●	○	○	○		Time limit		○				
26	Horizontal hinge pin roller bearing (114RS211) loaded, both sides spalled; inner side of outer race scored	Field (Unscheduled removal)		3,000	●	○	●	○	○	○	○		Time limit		○				
27	Inboard pitch varying roller bearing (114R-2130) corrosion; roller axial scoring, pitting, brinelling	Field (Unscheduled removal)		3,000		○	●	○	○	○	○		Time limit		○				

TABLE XXV - Continued

Test Key:
- ● Detected problem.
- ○ Can detect with adequate test duration.
- ◐ Can detect if artificial restraints are eliminated. Duration was adequate.
- × Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Bench Endur.	Whirl Tower	Tiedown	Flight Test	Eglin	Yuma	Alaska		Artificial Restraints	Inherent Restraints	Dynamic Systems				Inherent Restraints
28	Outboard pitch varying roller bearing (114R-2131) cage damage: axial scoring, and corrosion on raceway	Field (Unscheduled removal)		5,000		○	○	○	○	○	○		Time limit		○				
29	114R2052-1 rotor nut not reusable	Field (Maintenance)	Excess of installations: nylon insert wears	100		●	●	●	●	●	◐		Test acceptance criteria		○				
30	114R3116-42 flange bushing scuffed by pitch link rod end	Field (Maintenance)	Pitch link rotation	5,000		●	○	○	○	○	○		Time limit		○				
31	Spacer under rotor hub nut deleted at installation	Field (Safety)	Maintenance	100		●	●	●	●	●	◐		Maintenance procedure		○				

TABLE XXVI. FIELD AND TEST DETECTION COMPARISION OF RELIABILITY PROBLEMS FOR ROTOR BLADES

Test Key:
- ● Detected problem.
- ○ Can detect with adequate test duration.
- ● Can detect if artificial restraints are eliminated. Duration was adequate.
- × Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Whirl Tower	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Dynamic Systems				Inherent Restraints
1	Delaminations of rib tabs from fairing box skins	Field (Unscheduled removal)		500	●	●	●	●	●	●			Configuration		○				
2	End rib cracking (114R1068) and skin delamination	Field (Unscheduled removal)		1,000	×	×	○	×	○	●			Flight time limit	Loads on whirl tower, tiedown and Eglin	×				Loads
3	Tip cover cracking at leading edge and mounting area (114R1372)	Field (Maintenance)	Alternating air loads as blade rotates	500	×	×	○	×	●	○			Time limit	Forward velocity loads not present on tower, tiedown and Eglin	×				Forward velocity
4	Tip cover leading edge erosion (114P1372)	Field (Maintenance)		1,000	×	●	○	×	●	×			Time limit	Environment not present on whirl tower, Eglin and Alaska	×				Environment
5	Tip cover forward shear tie fitting cracking (114P1374)	Field (Unscheduled removal)		30,000	×	×	○	×	○	○			Time limit	Forward velocity loads not present in whirl, tiedown, and Eglin	×				Forward velocity
6	Trailing edge cracking	Field (Unscheduled removal)	Nicks on forward edge of trailing edge due to manufacturing procedures	30,000	●	○	●	●	●	●			Configuration not present. Time limit						

TABLE XXVI - Continued

Test Key:
- ● Detected problem.
- ○ Can detect with adequate test duration.
- ● Can detect if artificial restraints are eliminated. Duration was adequate.
- × Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Whirl Tower	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Dynamic Systems				Inherent Restraints
7	Root box to spar doubler unbonding	Field (Unscheduled removal)	Temperature and humidity effects on bonding system	30,000	×	×	×	●	×	×			Time limit	Environment not present	×				Environment
8	Internal surface of spar corroded	Field (Unscheduled removal)	Inadequate protective coating	1,000	●	●	○	○	○	○			Configuration not present on tiedown. Time limit		○				
9	Water entrapment in honeycomb (CH-47B blade) and subsequent delamination	Field (Unscheduled removal)		1,000	●	○	○	○	○	○			Time limit		○				
10	Fatigue crack at lower incident bolt hole in socket (114R1043)	Field (Safety)	Burr in hole	100,000	●	●	●	○	○	○			Configuration not present on whirl tower, tiedown, and flight test		○				
11	Erosion of skin in area of tiedown fitting	Field (Unscheduled removal)		1,000	×	○	○	×	●	×			Time limit on tiedown and flight tests	Environment not present on whirl tower, Eglin and Alaska	×				Environment
12	Delamination of doubler around tiedown fitting	Field (Unscheduled removal)	Damage due to improper use of pip pin and airflow	1,000	●	●	○	○	○	○			Time limit		○				
13	Spar crack	Field (Safety)	Loss of compressive residual stress from excess blade flapping	100,000	×	×	○	○	○	○			Time limit	Loads not present on whirl tower and tiedown	○				

TABLE XXVI - Continued

Test Key:
● Detected problem.
○ Can detect with adequate test duration.
● Can detect if artificial restraints are eliminated. Duration was adequate.
x Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Whirl Tower	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Dynamic Systems				Inherent Restraints
14	Blade socket incidence bolt corrosion	Field (Unscheduled removal)	Inadequate protective coating or material	30,000	○	●	○	○	○	○			Time limit		○				
15	Blade socket incidence bolt fretting	Field (Safety)		3,000	○	○	○	○	○	○			Time limit		○				
16	Leading edge erosion	Field (Unscheduled removal)		1,000	x	●	○	x	●	x			Time limit		x				
17	Corrosion of tip fitting studs	Test (Unscheduled removal)		5,000	●	●	●	●	●	●					○				
18	Erosion on bottom side of outboard box fairings	Test (Unscheduled removal)		1,000	x	●	○	x	○	x			Time limit on flight test and Yuma		x				
19	Blade skin delamination at trailing edge	Test (Unscheduled removal)	Skin ply orientation in error	3,000	●	●	●	●	●	●			Configuration not present		○				
20	Hysol filler flaking	Field (Maintenance)		1,000	●	●	○	○	○	○			Test acceptance criteria on whirl tower. Time limit		○				
21	Blade spar crack	Field (Safety)	Fatigue crack originating at lap in outer surface due to rolling process	100,000	○	○	○	○	○	○			Time limit		○				
22	Tip weight fitting unbonding	Field (Unscheduled removal)	Poor quality control	500	●	●	●	●	●	●			Configuration not present in tests		○				

TABLE XXVI - Continued

Test Key:
- ● Detected problem.
- O Can detect with adequate test duration.
- ● Can detect if artificial restraints are eliminated. Duration was adequate.
- × Cannot detect - due to inherent restraints.

Problem					Existing Test Techniques and Detection Potential										New Test Techniques and Detection Potential				
No.	Failure Mode	Source (and Impact)	Cause	MTBF (hr)	Whirl Tower	Tiedown	Flight Test	Eglin	Yuma	Alaska			Artificial Restraints	Inherent Restraints	Dynamic Systems				Inherent Restraints
23	Tip weight studs unbonded (CH-47B blade)	Field (Maintenance)	Poor quality control of bonding	10,000	●	●	●	●	●	●			Configuration not present in tests		O				
24	Tip cap nut. Plates pulled out (CH-47B blade)	Field (Maintenance)	Poor quality of bonding	3,000	●	●	●	●	●	●			Configuration not present in tests		O				
25	Water entrapment in blades	Test (Unscheduled removal)	Lack of drainage holes	100	●	●	●	●	●	●			Test acceptance criteria		O				
26	Rib tab to spar unbonding and cracking	Field (Unscheduled removal)	Manufacturing procedures in applying pressure to tabs	3,000	O	O	O	O	O	●			Time limit		O				

APPENDIX III

CH-47 TEST PROGRAM SCHEDULES

This appendix details the test history for each of the eight components in the major dynamic system of the CH-47A, B and C helicopters. For each component, a separate schedule is shown for each of the three test types investigated:

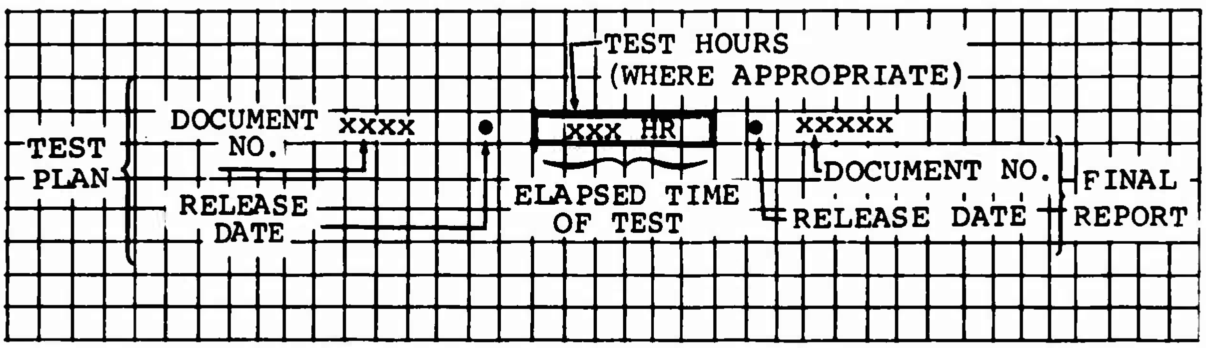
Type I - Analytical methods confirmation (general design development)

Type II - Problem identification

Type IV - Problem investigation

This data was used to identify each test performed and its corresponding test report document number. The data from these reports provided the test detection history in Appendix I.

A sample legend for the schedules is presented below.



The first sheet (Figure 60) is a summary of the problem identification tests. It also shows the cumulative test and fleet operating hours.

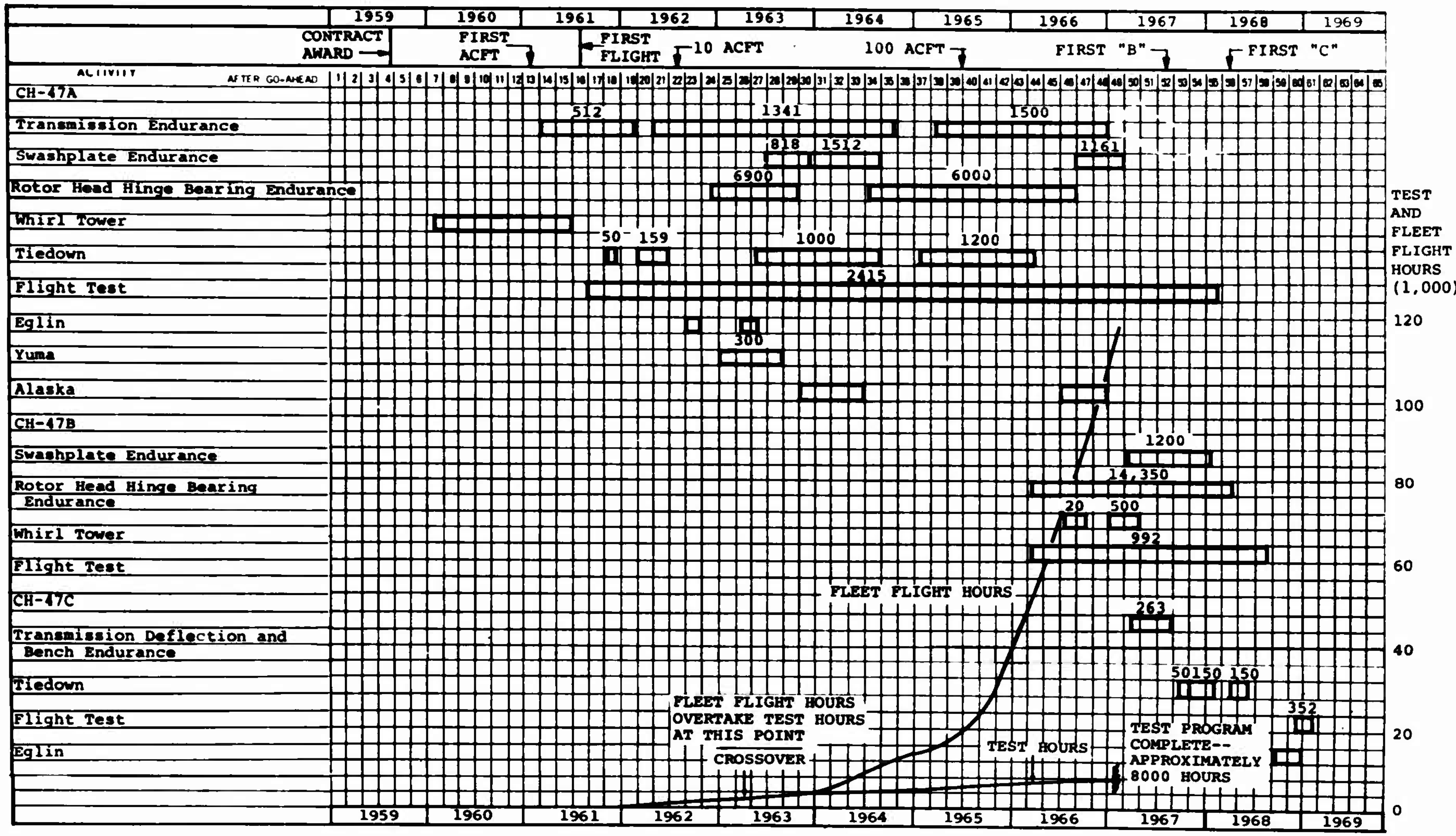


Figure 60. Summary of Flight and Test Hours for CH-47 Problem Identification Test Program.

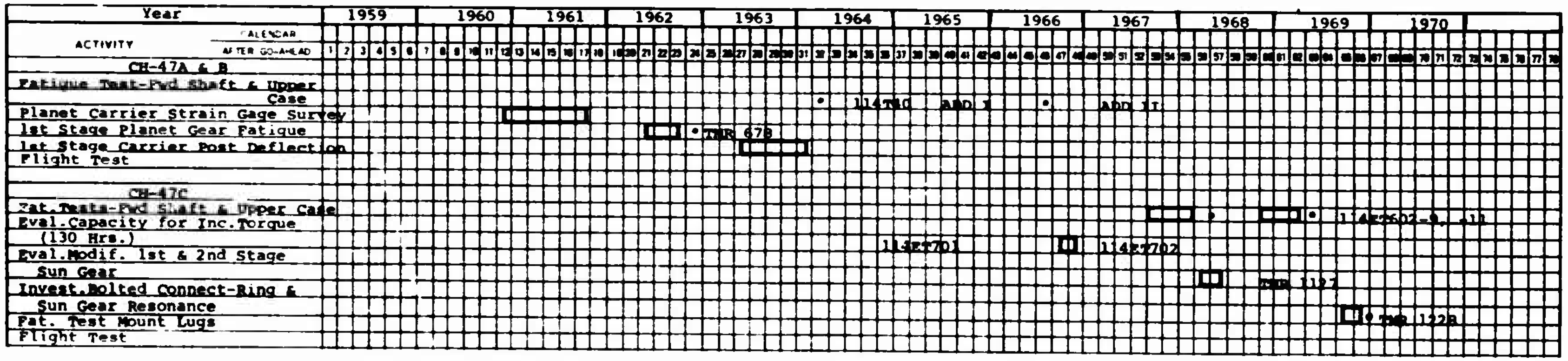


Figure 61. Design Development Test Schedule for CH-47A, B and C Forward Transmissions.

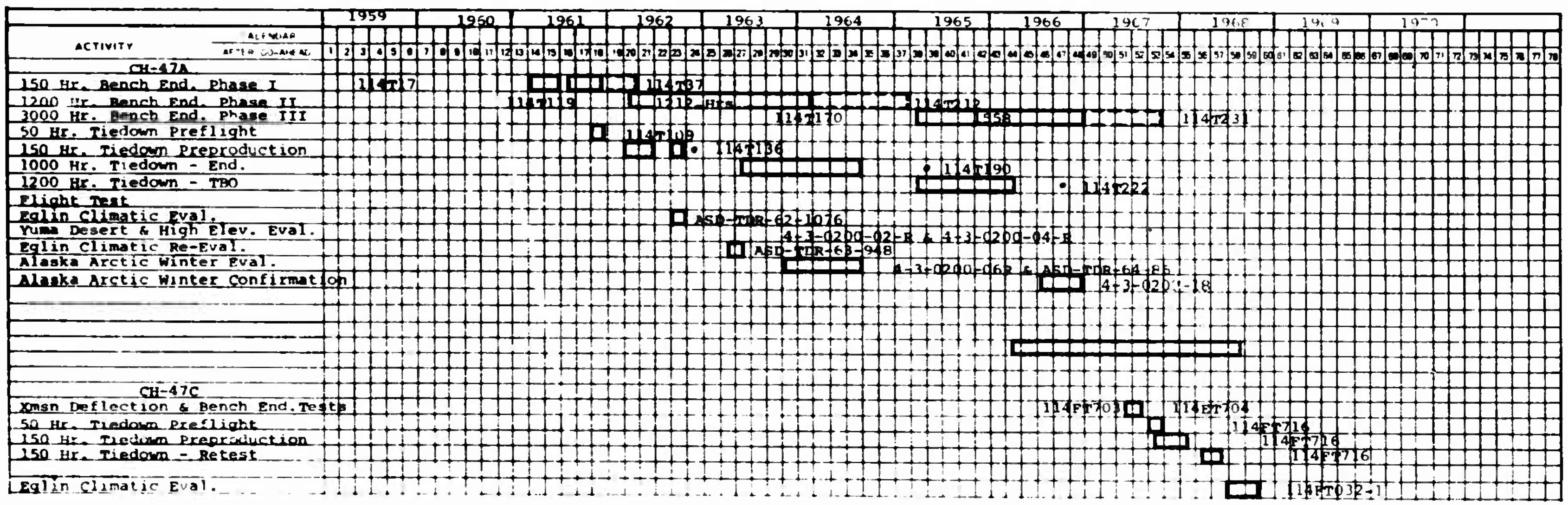


Figure 62. Problem Identification Test Schedule for CH-47A, B and C Forward Transmissions.

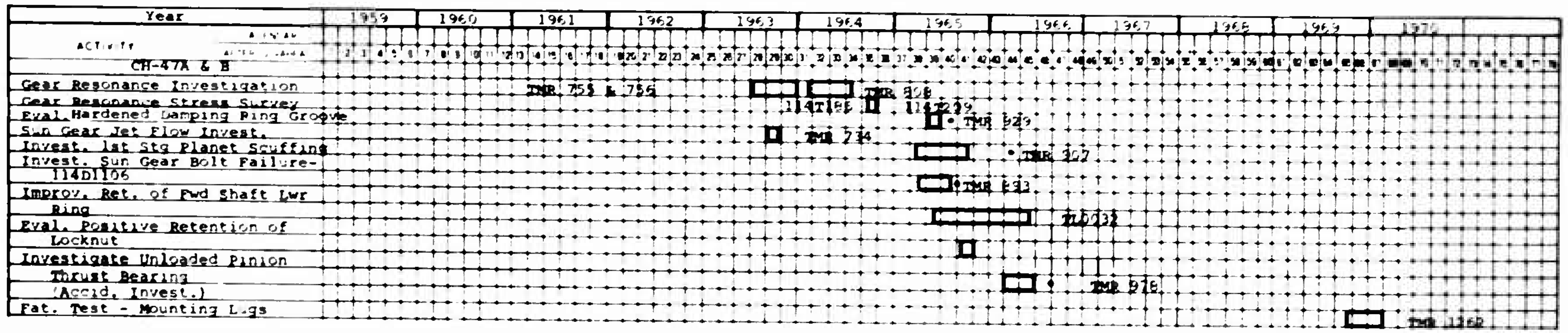


Figure 63. Problem Investigation Test Schedule for CH-47A, B and C Forward Transmissions.

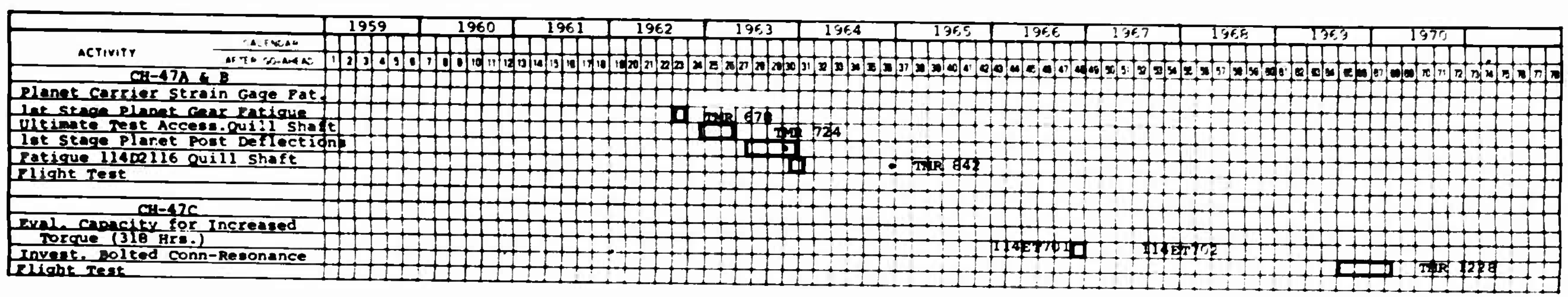


Figure 64. Design Development Test Schedule for CH-47A, B and C Aft Transmissions.

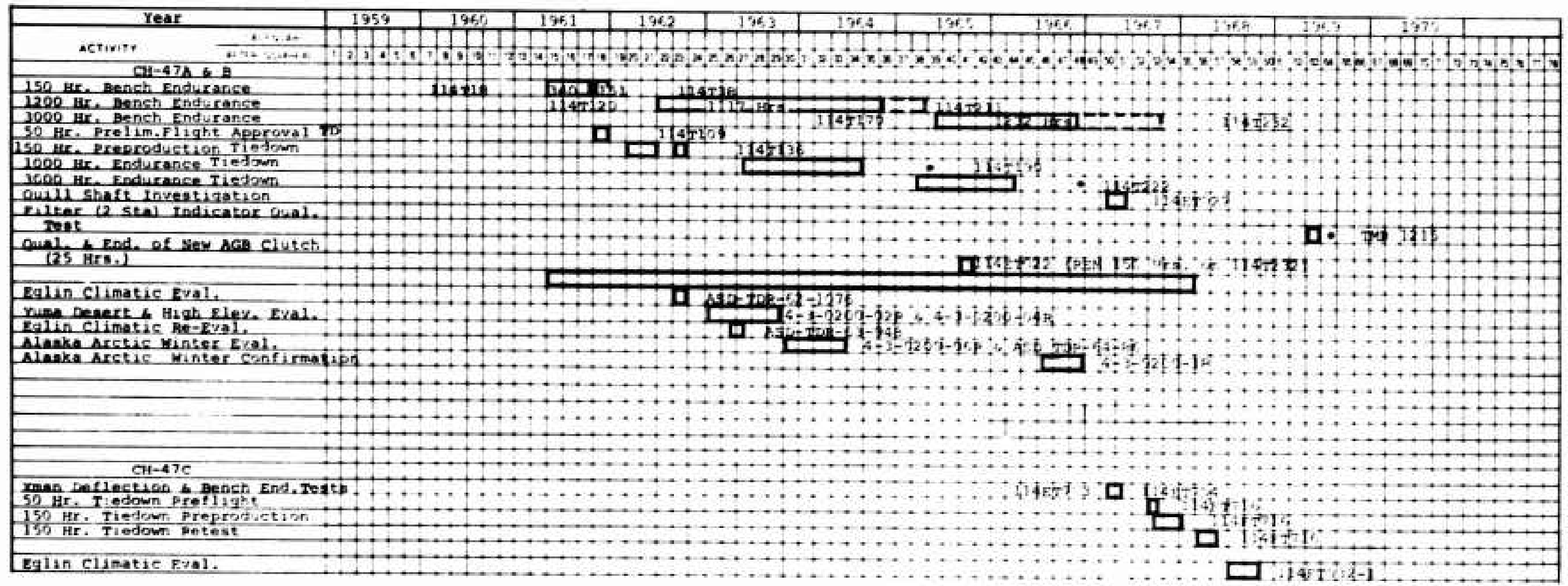


Figure 65. Problem Identification Test Schedule for CH-47A, B and C Aft Transmissions.

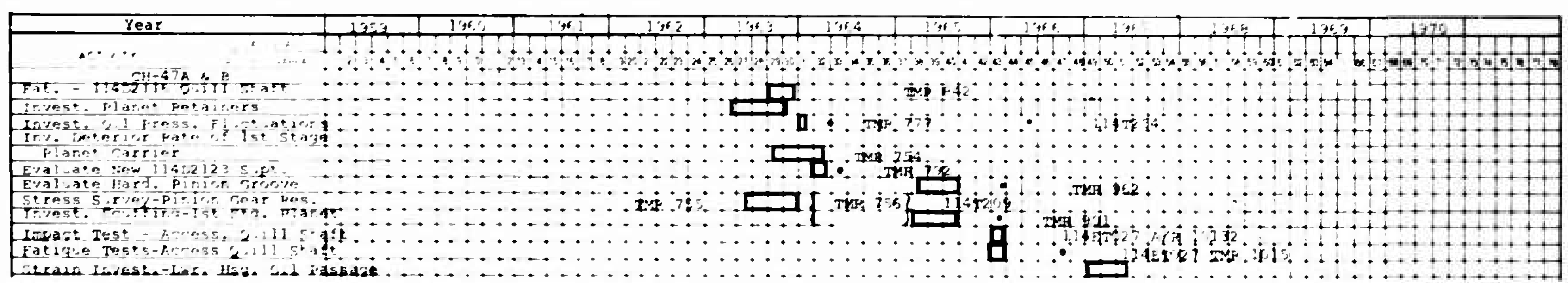


Figure 66. Problem Investigation Test Schedule for CH-47A, B and C Aft Transmissions.

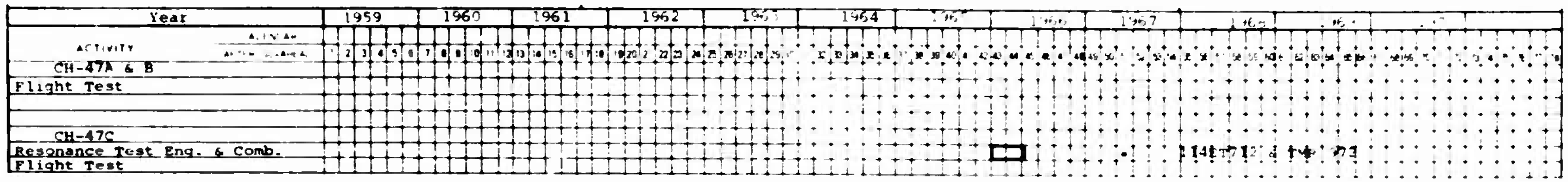


Figure 67. Design Development Test Schedule for CH-47A, B and C Combining Transmissions.

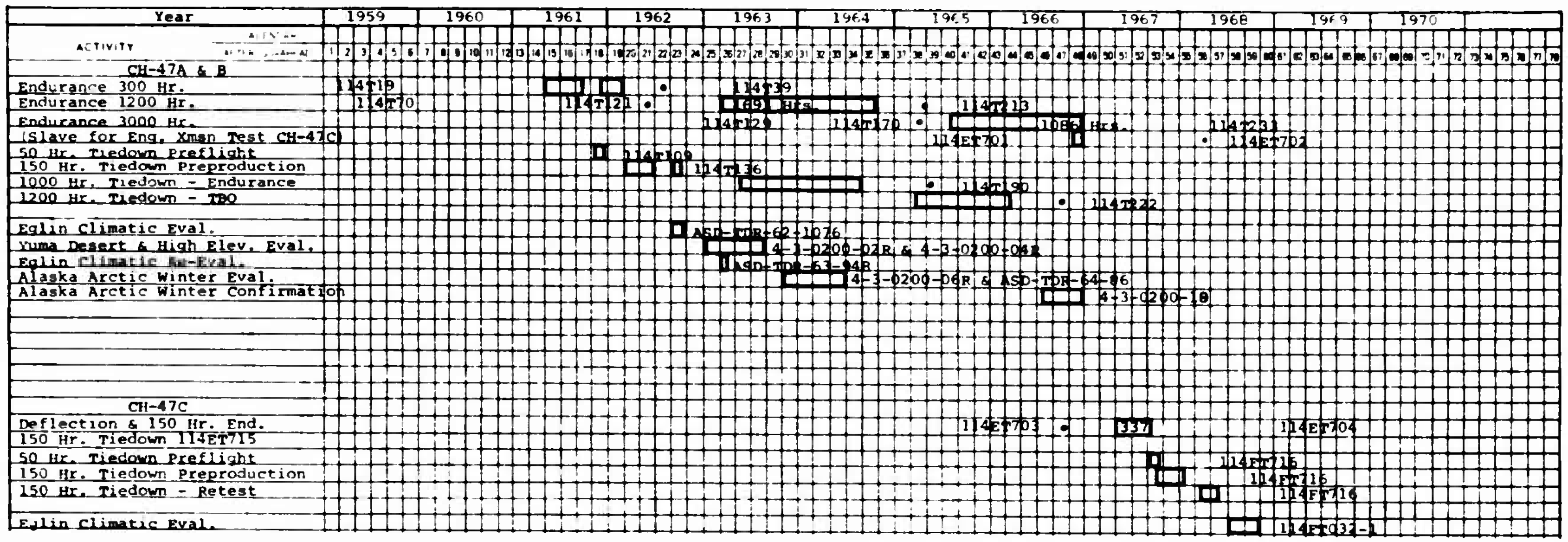


Figure 68. Problem Identification Test Schedule for CH-47A, B and C Combining Transmissions.

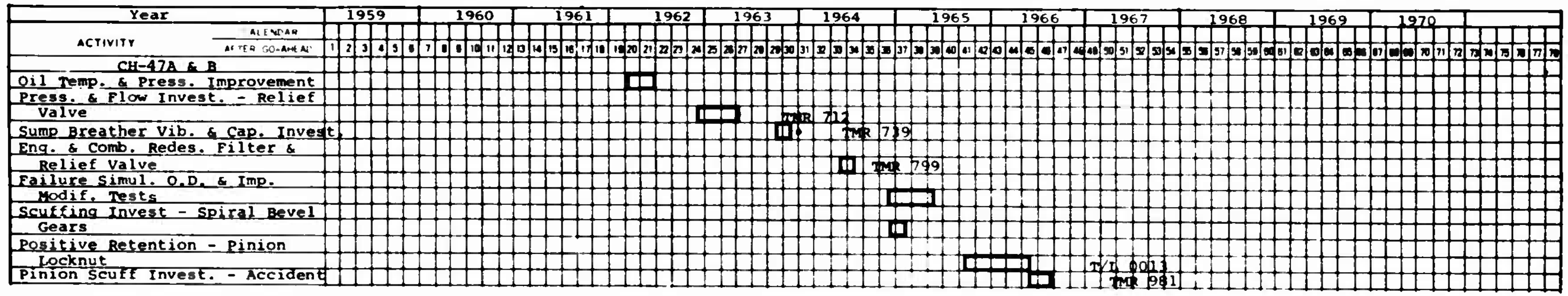


Figure 69. Problem Investigation Test Schedule for CH-47A, B and C Combining Transmissions.

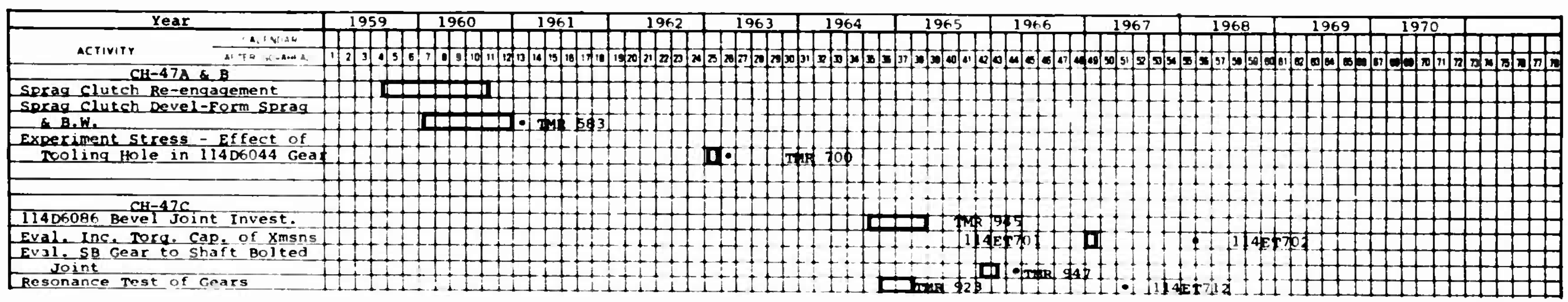


Figure 70. Design Development Test Schedule for CH-47A, B and C Engine Transmissions.

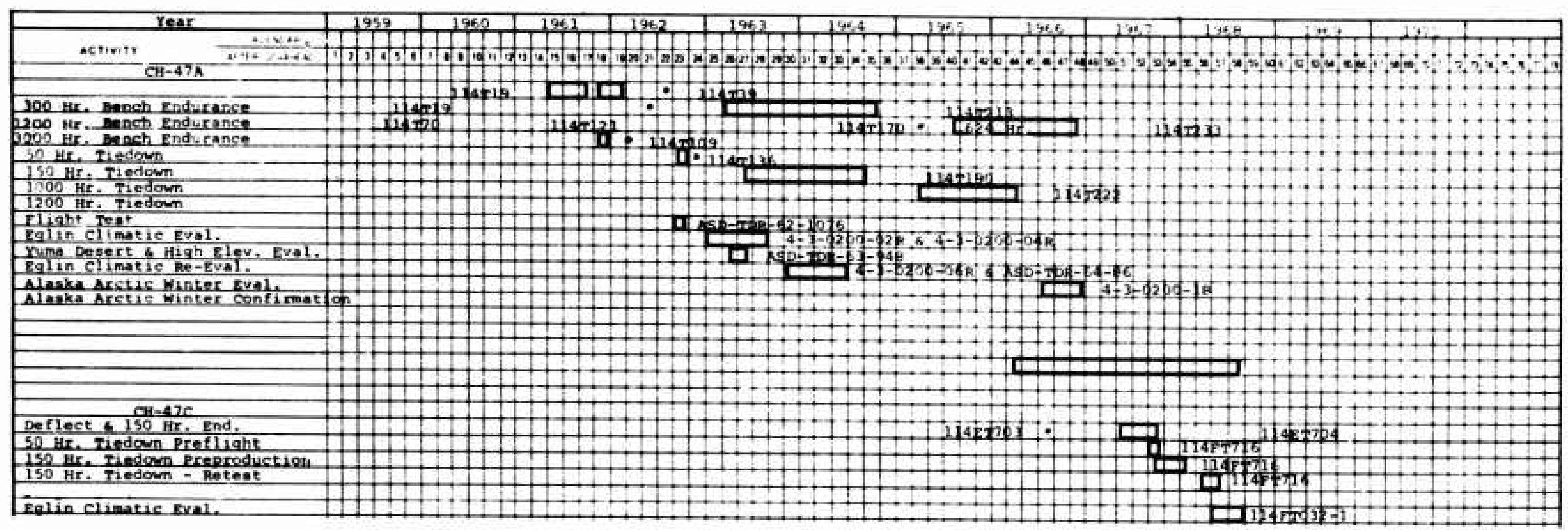


Figure 71. Problem Identification Test Schedule for CH-47A, B and C Engine Transmissions.

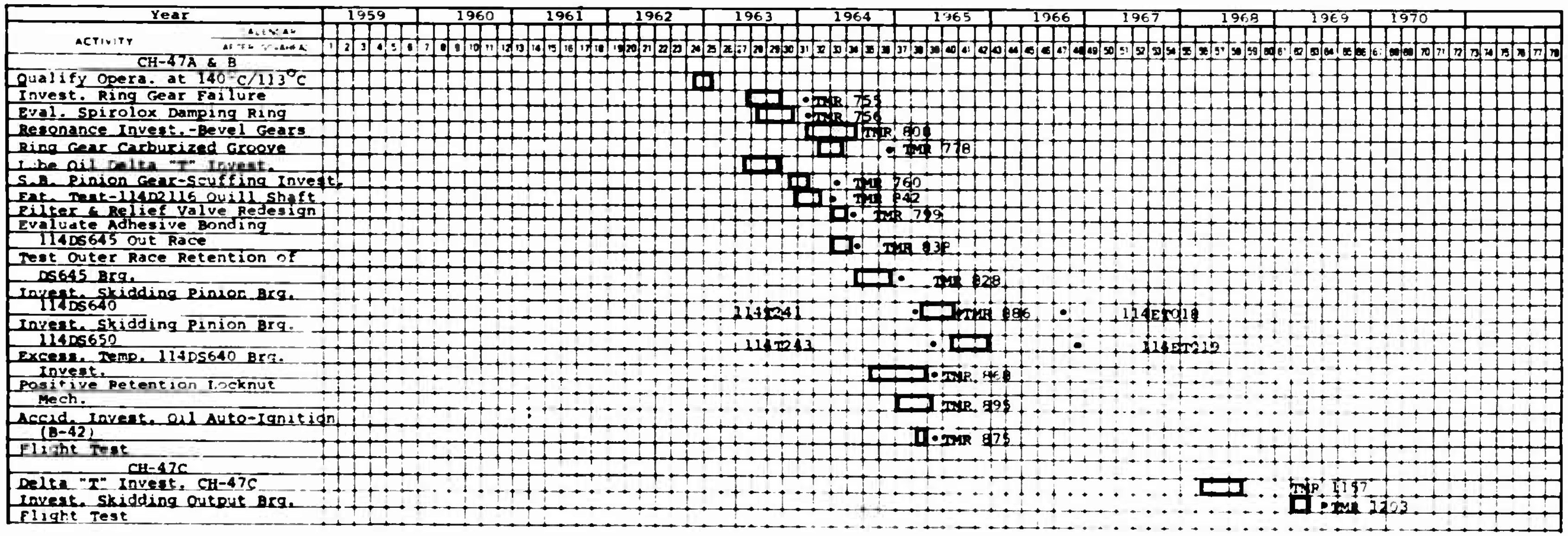


Figure 72. Problem Investigation Test Schedule for CH-47A, B and C Engine Transmissions.

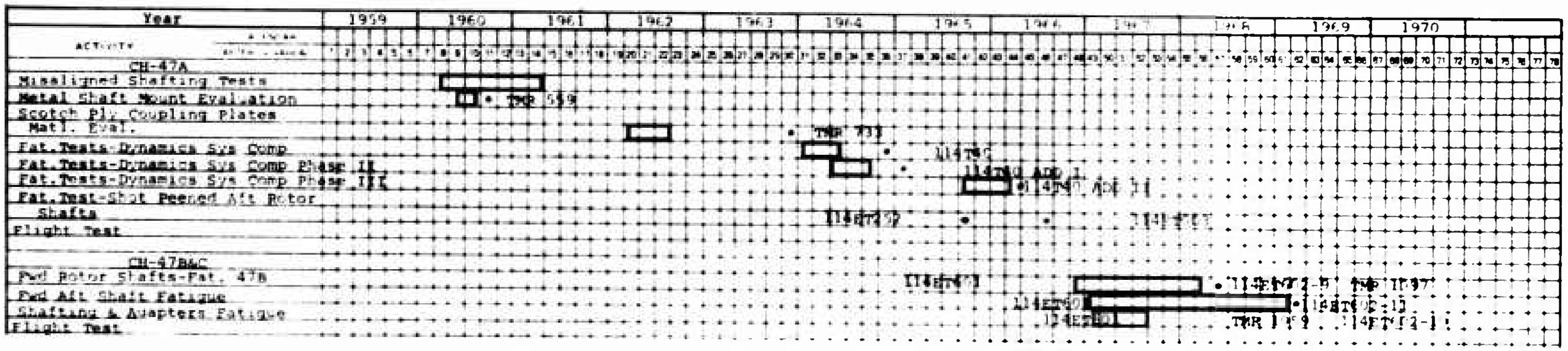


Figure 73. Design Development Test Schedule for CH-47A, B and C Drive Shafting.

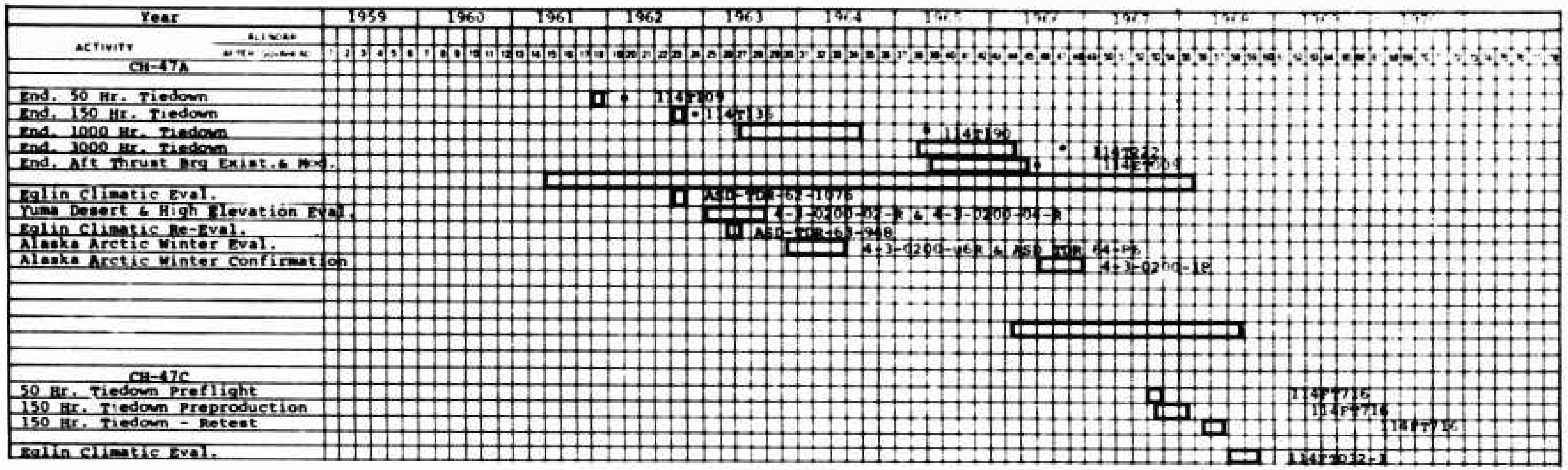


Figure 74. Problem Identification Test Schedule for CH-47A, B and C Drive Shafting.

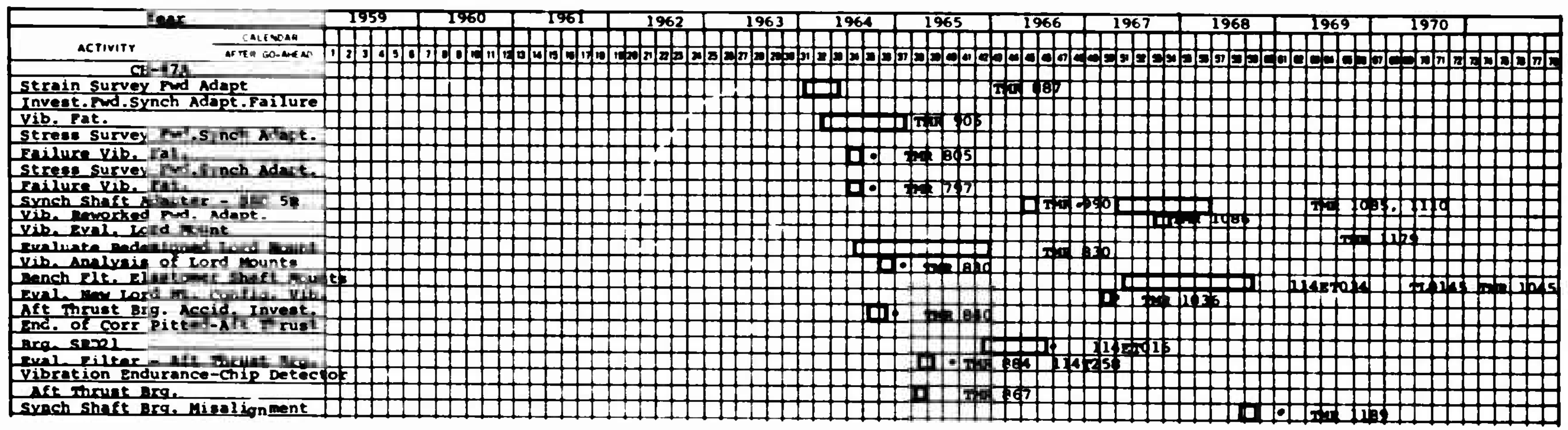


Figure 75. Problem Investigation Test Schedule for CH-47A, B and C Drive Shafting.

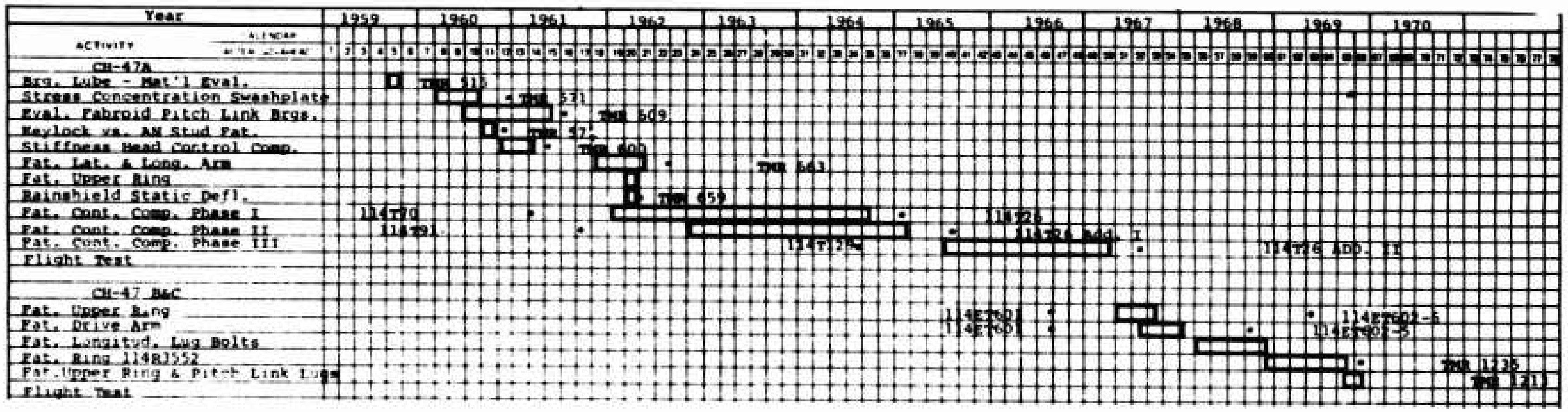


Figure 76. Design Development Test Schedule for CH-47A, B and C Rotor Controls.

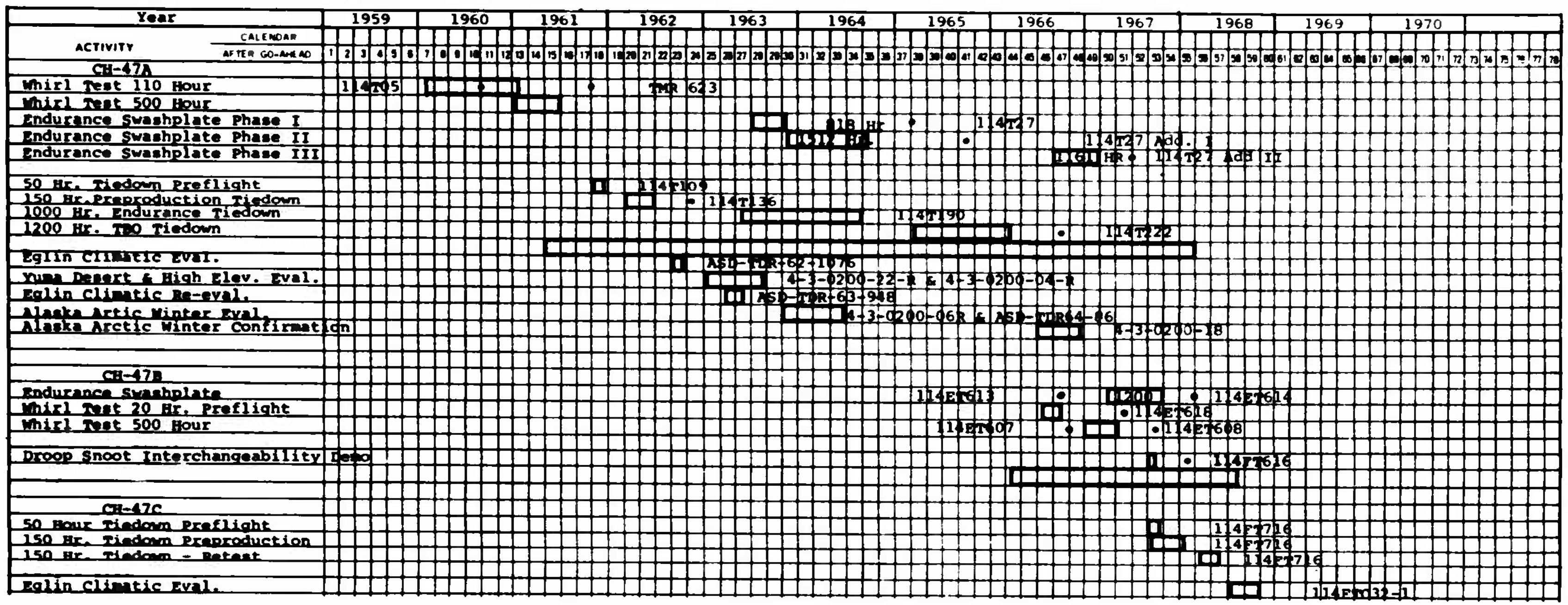


Figure 77. Problem Identification Test Schedule for CH-47A, B and C Rotor Controls.

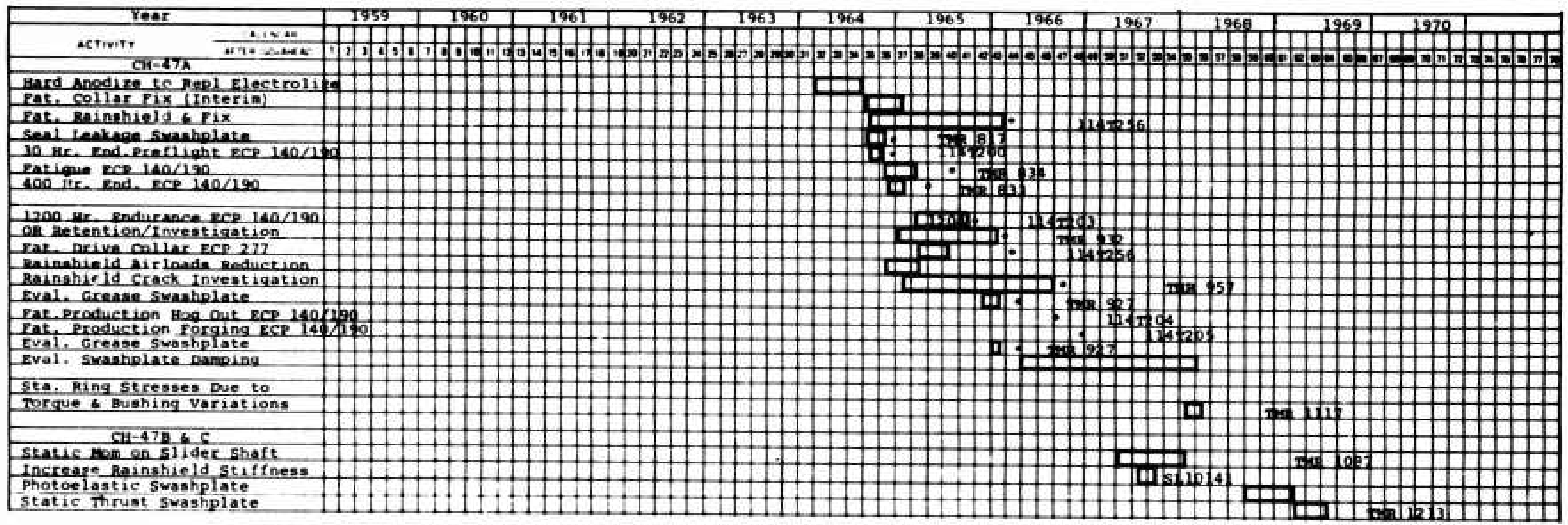


Figure 78. Problem Investigation Test Schedule for CH-47A, B and C Rotor Controls.

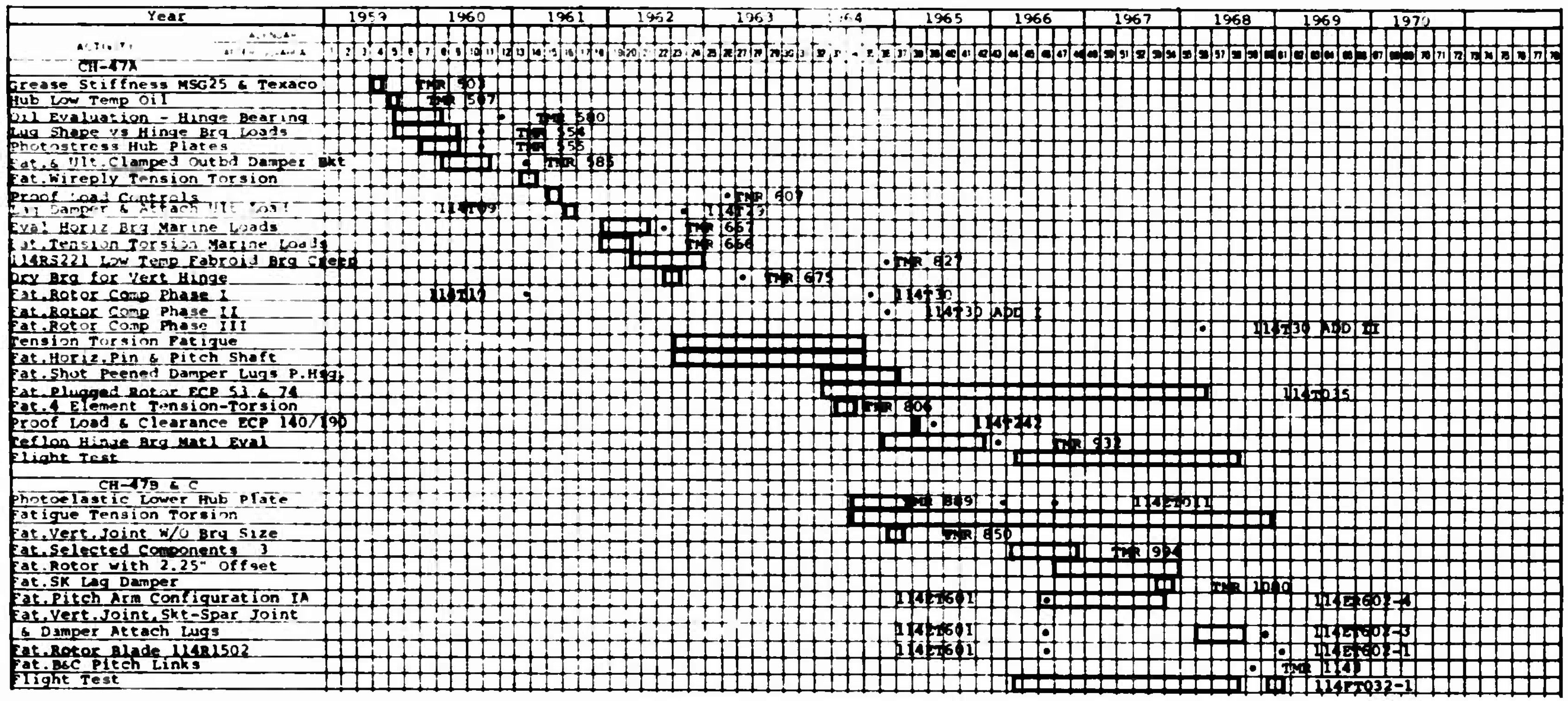


Figure 79. Design Development Test Schedule for CH-47A, B and C Rotor Hubs.

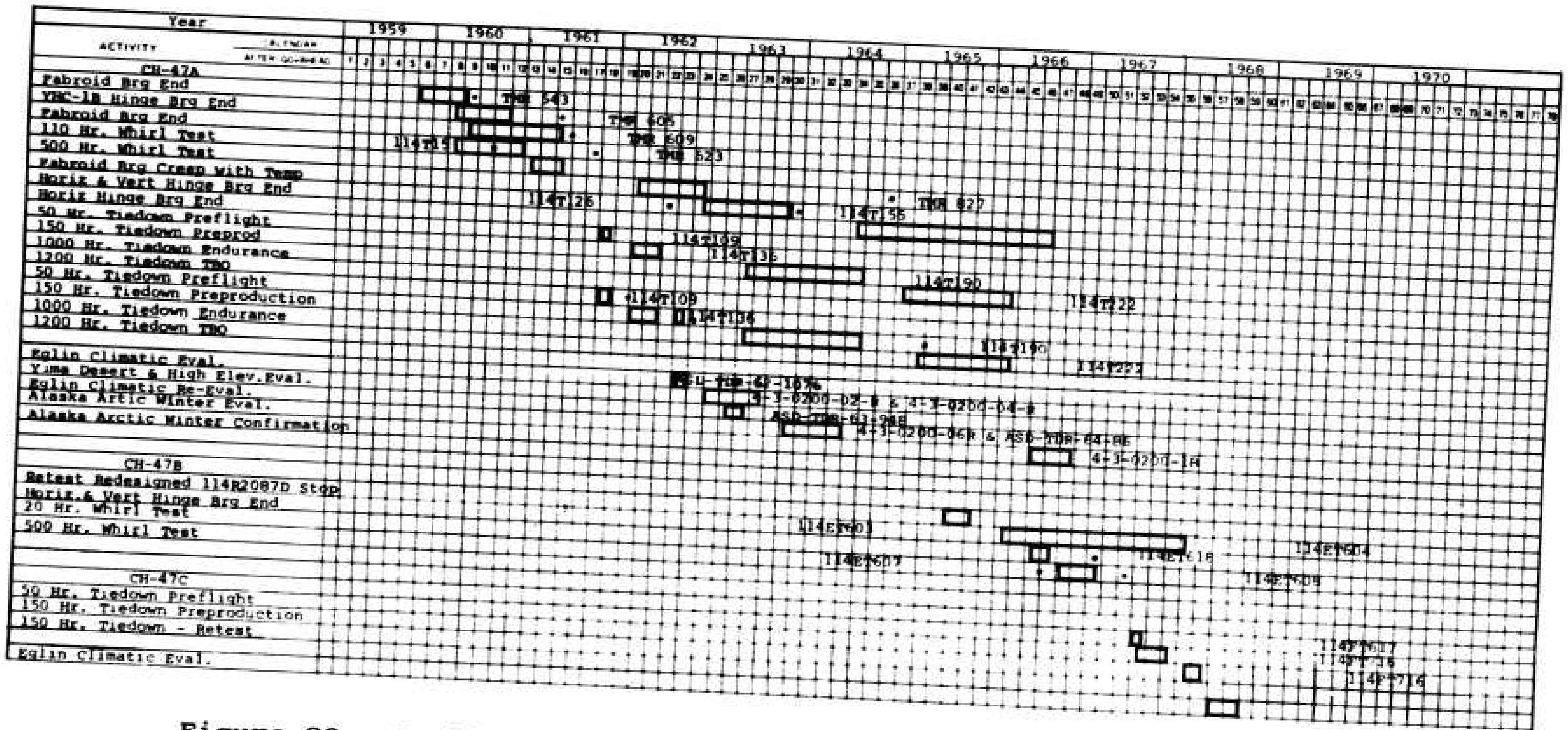


Figure 80. Problem Identification Test Schedule for CH-47A, B and C Rotor Hubs.

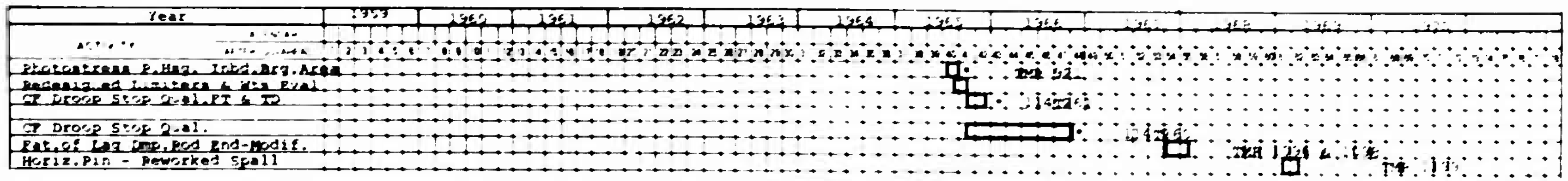


Figure 81. Problem Investigation Test Schedule for CH-47A, B and C Rotor Hubs.

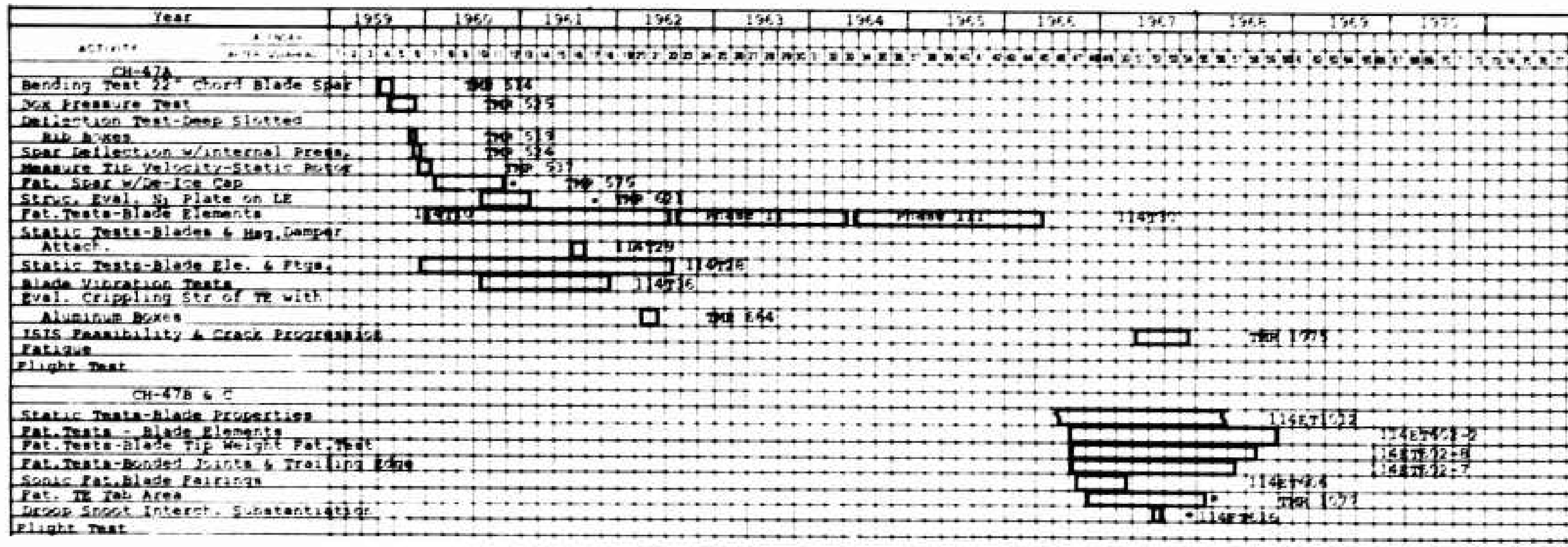


Figure 82. Design Development Test Schedule for CH-47A, B and C Rotor Blades.

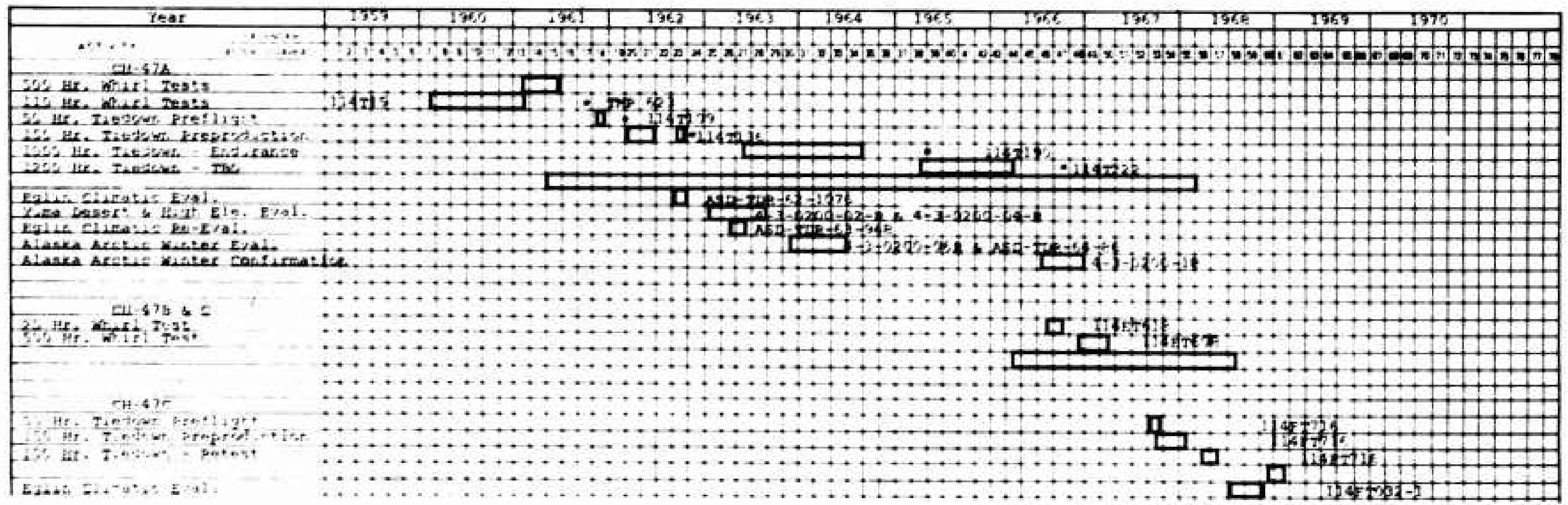


Figure 83. Problem Identification Test Schedule for CH-47A, B and C Rotor Blades.

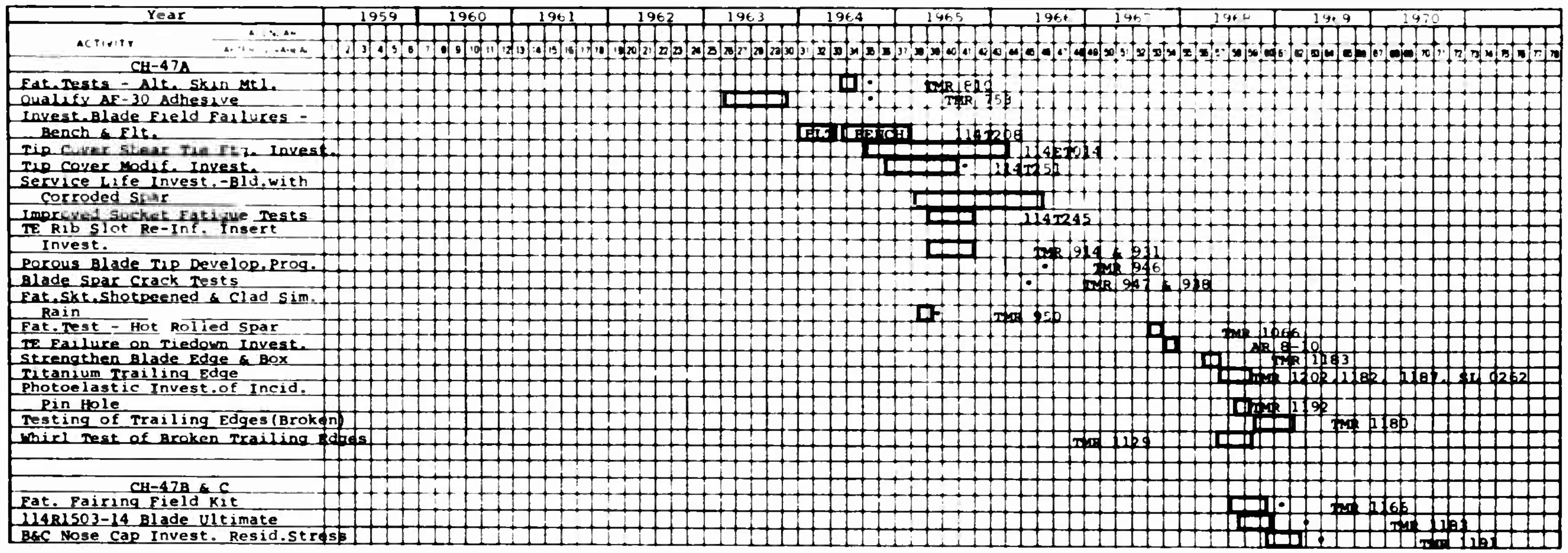


Figure 84. Problem Investigation Test Schedule for CH-47A, B and C Rotor Blades.

APPENDIX IV

PROBLEM IDENTIFICATION TEST PROGRAM WORKSHEETS FOR HELICOPTER "A"

This appendix presents selected worksheets on which are calculated the reliability and costs of test programs for Helicopter "A". The data from these programs is used to construct the costs vs required MTBR plots on Figures 29, 30, and 31.

As shown in the sample below, the title of each figure contains a code which indicates the characteristics of the programs.

3-YEAR
ELAPSED TIME

3 A 52

TYPE OF PROGRAM

A: BENCH AND FLIGHT TEST
B: DYNAMIC SYSTEM AND FLIGHT TEST
C: ALL FLIGHT TEST

LOWEST REQUIRED MTBR OF
COMPONENTS (IN 100 HOURS):
52 = 5200 HOURS
7.2 = 720 HOURS

It should be noted that the MTBR's of the rotor controls and rotor hub are combined into a single MTBR reflecting the integrated nature of the current design.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Test Technique Code
Main Xmsn Gearbox	600	1500 + 2500*	Type I Flight Test + Closed Loop	2
Main Xmsn Controls	600	1500 + 850*	Type I Flight Test + Swashplate Bench*	5
Main Xmsn Hub		1500*	Type I Flight Test*	7
Intermediate Box	1200	1500	Type I Flight Test	
Tail Rotor Xmsn	670	1500	Type I Flight Test	
Main Rotor Blades	2300	1500	Type I Flight Test	
Tail Rotor Blades	6700	1500	Type I Flight Test	
Tail Drive Shaft	670	1500	Type I Flight Test	
Tail Rotor Hub	1500	1500	Type I Flight Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1		20	200			2000K		580		
2	2500	18	400	6.3 / 1	24.3	1300K	1300	280	700	2000
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5	850	6	500	1.7 / 1	7.7	100K	100	40	34	134
6			70					2500		
7	1500		20					NC		NC
Total Problem Identification Test Cost										2,134

*Test technique and hours associated with Code No.

Figure 85. Trade-Off Study Worksheet for Problem Identification Test Programs No. 3A6, 4A6 and 6A6.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Code
Main Xmsn Gearbox	720	1500 + 3400*	Type I Flight Test + Closed Loop*	2
Main Xmsn Controls	720	1500 1400*	Type I Flight Test + Swashplate Bench*	5
Main Xmsn Hub		1500*	Type I Flight Test*	7
Intermediate Box	1480	1500 + 400*	Type I Flight Test + Tail Rotor Stand*	4
Tail Rotor Xmsn	720	1500 + 400	Type I Flight Test + Tail Rotor Stand	
Main Rotor Blades	2300	1500	Type I Flight Test	
Tail Rotor Blades	8060	1500 + 400	Type I Flight Test + Tail Rotor Stand	
Tail Drive Shaft	720	1500 + 400	Type I Flight Test + Tail Rotor Stand	
Tail Rotor Hub	1860	1500 + 400	Type I Flight Test + Tail Rotor Stand	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/HrK	Oper Cost $K	Total Cost $K
1		20	200			2000K		580		
2	3400	18	400	8.5 / 1	26.5	1300K	1300	280	952	2252
3		20	350			560K 2600K		220		
4	400	16	400	1.0 / 1	17.0	330K	330	110	44	374
5	1400	6	500	2.8 / 1	8.8	100K	100	40	56	156
6			70					2500		
7	1500		20					NC		NC
Total Problem Identification Test Cost										2,782

*Test technique and hours associated with Code No.

Figure 86. Trade-Off Study Worksheet for Problem Identification Test Program No. 3A7.2.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Test Technique Code
Main Xmsn Gearbox	3000	3700 + 12,000*	Type I & II Flt. Test + Closed Loop*	2
Main Xmsn Controls	3000	3700+3400 +7200*	Type I&II Flt Test + Whl Twr + Swhplt Bench*	5
Main Xmsn Hub		3700 + 3400*	Type I & II Flight Test + Whirl Tower*	3
Intermediate Box	5300	3700* + 2800	Type I & II Flight Test* + Tail Rotor Stand	6&7
Tail Rotor Xmsn	3000	3700 + 2800*	Type I & II Flight Test + Tail Rotor Stand*	4
Main Rotor Blades	8800	3700 + 3400	Type I &II Flight Test + Whirl Tower	
Tail Rotor Blades	10,000	3700 + 2800	Type I & II Flight Test + Tail Rotor Stand	
Tail Drive Shaft	7140	3700 + 2800	Type I & II Flight Test + Tail Rotor Stand	
Tail Rotor Hub	4780	3700 + 2800	Type I & II Flight Test + Tail Rotor Stand	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1		20	200			2000K		580		
2	12,000	18	400	15.0 / 2	33.0	1300K	2600	280	3360	5960
3	3400	20	350	9.7 / 1	29.7	560K 2600K	560	220	748	1308
4	2800	16	400	7.0 / 1	23.0	330K	330	110	308	638
5	7200	6	500	14.4 / 1	20.4	100K	100	40	288	388
6	2200		70					2500	5500	5500
7	1500		20					NC		NC
Total Problem Identification Test Cost										13,794

*Test technique and hours associated with Code No.

Figure 87. Trade-Off Study Worksheet for Problem Identification Test Program No. 3A30.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique	
			Name	Code
Main Xmsn Gearbox	3000	3700 + 12,000*	Type I & II Flight Test + Closed Loop*	2
Main Xmsn Controls	3000	3700+3400 +7200*	Type I & II Flt Test + Whl Twr + Swhplt Bench*	5
Main Xmsn Hub		3700 + 3400*	Type I & II Flight Test + Whirl Tower*	3
Intermediate Box	5300	3700* + 2800	Type I & II Flight Test + Tail Rotor Stand	6&7
Tail Rotor Xmsn	3000	3700 + 2800*	Type I & II Flight Test + Tail Rotor Stand	4
Main Rotor Blades	8800	3700 + 3400	Type I & II Flight Test + Whirl Tower	
Tail Rotor Blades	10,000	3700 + 2800	Type I & II Flight Test + Tail Rotor Stand	
Tail Drive Shaft	7140	3700 + 2800	Type I & II Flight Test + Tail Rotor Stand	
Tail Rotor Hub	4780	3700 + 2800	Type I & II Flight Test + Tail Rotor Stand	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr K	Oper Cost $K	Total Cost $K
1		20	200			2000K		580		
2	12,000	18	400	30.0/1	48.0	1300K	1300	280	3360	4660
3	3400	20	350	9.7/1	29.7	560K 2600K	560	220	748	1308
4	2800	16	400	7.0/1	23.0	330K	330	110	308	638
5	7200	6	500	14.4/1	20.4	100K	100	40	288	388
6	2200		70					2500	5500	5500
7	1500		20					NC		NC
Total Problem Identification Test Cost										12,494

*Test technique and hours associated with Code No.

Figure 88. Trade-Off Study Worksheet for Problem Identification Test Programs No. 4A30 and 6A30.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Test Technique Code
Main Xmsn Gearbox	5200	7500 + 14,400*	Type I & II Flt. Test + Closed Loop*	2
Main Xmsn Controls	5200	7500+1800 + 1450*	Type I & II Flt. Test + Whl Twr + Swhplt Bench	5
Main Xmsn Hub		1800*	Type I & II Flight Test + Whirl Tower*	3
Intermediate Box	16,200	7500*	Type I & II Flight Test*	6&7
Tail Rotor Xmsn	5200	7500	Type I & II Flight Test	
Main Rotor Blades	10,000	7500 + 1800	Type I & II Flight Test + Whirl Tower	
Tail Rotor Blades	10,000	7500	Type I & II Flight Test	
Tail Drive Shaft	10,400	7500	Type I & II Flight Test	
Tail Rotor Hub	6500	7500	Type I & II Flight Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1		20	200			2000K		580		
2	14,400	18	400	18.0 / 2	36	1300K	2600	280	4032	6632
3	1800	20	350	5.1 / 1	25.1	560K 2600K	560	220	396	956
4		16	400			330K		110		
5	1450	6	500	2.9 / 1	8.9	100K	100	40	58	158
6	6000		70					2500	15,000	15,000
7	1500		20					NC		NC
Total Problem Identification Test Cost										22,746

*Test technique and hours associated with Code No.

Figure 89. Trade-Off Study Worksheet for Problem Identification Test Program No. 3A52.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique: Name	Test Technique: Code
Main Xmsn Gearbox	5200	6000 + 22,600*	Type I & II Flight Test + Closed Loop*	2
Main Xmsn Controls	5200	6000+4200 +2150*	Type I & II Flt. Test + Whl Twr + Swhplt Bench*	5
Main Xmsn Hub		6000 + 4200*	Type I & II Flt. Test + Whirl Tower*	3
Intermediate Box	9430	6000* + 1900	Type I & II Flt. Test* + Tail Rotor Stand	6&7
Tail Rotor Xmsn	5200	6000 + 1900*	Type I & II Flt. Test + Tail Rotor Stand	4
Main Rotor Blades	10,400	6000 + 4200	Type I & II Flt. Test + Whirl Tower	
Tail Rotor Blades	10,000	6000 + 1900	Type I & II Flt. Test + Tail Rotor Stand	
Tail Drive Shaft	10,700	6000 + 1900	Type I & II Flt. Test + Tail Rotor Stand	
Tail Rotor Hub	6540	6000 + 1900	Type I & II Flt. Test + Tail Rotor Stand	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1		20	200			2000K		580		
2	22,600	18	400	28.3 / 2	46.3	1300K	2600	280	6048	8648
3	4200	20	350	12.1 / 1	32.0	560K 2600K	560	220	924	1484
4	1900	16	400	4.8 / 1	20.8	330K	330	110	209	539
5	2150	6	500	4.3 / 1	10.3	100K	100	40	86	186
6	4500		70					2500	11,250	11,250
7	1500		20					NC		NC
Total Problem Identification Test Cost										22,107

*Test technique and hours associated with Code No.

Figure 90. Trade-Off Study Worksheet for Problem Identification Test Program No. 4A52.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique	
			Name	Code
Main Xmsn Gearbox	5200	6000 + 22,600*	Type I & II Flt. Test + Closed Loop*	2
Main Xmsn Controls	5200	6000+4200 +2150*	Type I & II Flt. Test + Whl Twr + Shwplt Bench*	5
Main Xmsn Hub		6000 + 4200*	Type I & II Flt. Test + Whirl Tower*	3
Intermediate Box	9430	6000* + 1900	Type I & II Flt. Test* + Tail Rotor Stand	6&7
Tail Rotor Xmsn	5200	6000 + 1900*	Type I & II Flt. Test + Tail Rotor Stand	4
Main Rotor Blades	10,400	6000 + 4200	Type I & II Flt. Test + Whirl Tower	
Tail Rotor Blades	10,000	6000 + 1900	Type I & II Flt. Test + Tail Rotor Stand	
Tail Drive Shaft	10,700	6000 + 1900	Type I & II Flt. Test + Tail Rotor Stand	
Tail Rotor Hub	6540	6000 + 1900	Type I & II Flt. Test + Tail Rotor Stand	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1		20	200			2000K		580		
2	22,600	18	400	54.0/1	72.0	1300K	1300	280	6048	7348
3	4200	20	350	12.1/1	32.0	560K 2600K	560	220	924	1484
4	1900	16	400	4.8/1	20.8	330K	330	110	209	539
5	2150	6	500	4.3/1	10.3	100K	100	40	86	186
6	4500		70					2500	11,250	11,250
7	1500		20					NC		NC
Total Problem Identification Test Cost										20,807

*Test technique and hours associated with Code No.

Figure 91. Trade-Off Study Worksheet for Problem Identification Test Program No. 6A52.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique	
			Name	Code
Main Xmsn Gearbox	600	1500 + 2300*	Type I Flight Test + Dynamic Systems Test*	1
Main Xmsn Controls	890	1500* + 2300	Type I Flight Test* + Dynamic Systems Test	7
Main Xmsn Hub		1500 + 2300	Type I Flight Test + Dynamic Systems Test	
Intermediate Box	2300	1500 + 2300	Type I Flight Test + Dynamic Systems Test	
Tail Rotor Xmsn	1100	1500 + 2300	Type I Flight Test + Dynamic Systems Test	
Main Rotor Blades	4000	1500 + 2300	Type I Flight Test + Dynamic Systems Test	
Tail Rotor Blades	10,000	1500 + 2300	Type I Flight Test + Dynamic Systems Test	
Tail Drive Shaft	2200	1500 + 2300	Type I Flight Test + Dynamic Systems Test	
Tail Rotor Hub	2900	1500 + 2300	Type I Flight Test + Dynamic Systems Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1	2300	20	200	11.5/1	31.5	2000K	2000	580	1334	3334
2		18	400			1300K		280		
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5		6	500			100K		40		
6			70					2500		
7	1500		20					NC		NC
Total Problem Identification Test Cost										3334

*Test technique and hours associated with Code No.

Figure 92. Trade-Off Study Worksheet for Problem Identification Test Programs No. 3B6, 4B6, and 6B6.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Code
Main Xmsn Gearbox	3000	2900 + 9600*	Type I & II Flt. Test + Dynamic Systems Test*	1
Main Xmsn Controls	3190	2900* + 9600	Type I & II Flt. Test* + Dynamic Systems Test	6&7
Main Xmsn Hub		2900 + 9600	Type I & II Flt. Test + Dynamic Systems Test	
Intermediate Box	10,000	2900 + 9600	Type I & II Flt. Test + Dynamic Systems Test	
Tail Rotor Xmsn	3750	2900 + 9600	Type I & II Flt. Test + Dynamic Systems Test	
Main Rotor Blades	10,000	2900 + 9600	Type I & II Flt. Test + Dynamic Systems Test	
Tail Rotor Blades	10,000	2900 + 9600	Type I & II Flt. Test + Dynamic Systems Test	
Tail Drive Shaft	9000	2900 + 9600	Type I & II Flt. Test + Dynamic Systems Test	
Tail Rotor Hub	8800	2900 + 9600	Type I & II Flt. Test + Dynamic Systems Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1	9600	20	200	16.0 / 3	36	2000K	6000	580	5568	11,568
2		18	400			1300K		280		
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5		6	500			100K		40		
6	1400		70					2500	3500	3500
7	1500		20					NC		NC
Total Problem Identification Test Cost										15,068

*Test technique and hours associated with Code No.

Figure 93. Trade-Off Study Worksheet for Problem Identification Test Program No. 3B30.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique	
			Name	Code
Main Xmsn Gearbox	3000	2100 + 11,200*	Type I & II Flight Test +Dynamic Systems Test*	1
Main Xmsn Controls	3000	2100* + 11,200	Type I & II Flight Test* +Dynamic Systems Test	6&7
Main Xmsn Hub		2100 + 11,200	Type I & II Flight Test + Dynamic Systems Test	
Intermediate Box	10,000	2100 + 11,200	Type I & II Flight Test + Dynamic Systems Test	
Tail Rotor Xmsn	3550	2100 + 11,200	Type I & II Flight Test + Dynamic Systems Test	
Main Rotor Blades	10,000	2100 + 11,200	Type I & II Flight Test + Dynamic Systems Test	
Tail Rotor Blades	10,000	2100 + 11,200	Type I & II Flight Test + Dynamic Systems Test	
Tail Drive Shaft	7500	2100 + 11,200	Type I & II Flight Test + Dynamic Systems Test	
Tail Rotor Hub	8100	2100 + 11,200	Type I & II Flight Test + Dynamic Systems Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1	11,200	20	200	28.0 / 2	48.0	2000K	4000	580	6496	10,496
2		18	400			1300K		280		
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5		6	500			100K		40		
6	600		70					2500	1500	1500
7	1500		20					NC		NC
Total Problem Identification Test Cost										11,996

*Test technique and hours associated with Code No.

Figure 94. Trade-Off Study Worksheet for Problem Identification Test Program No. 4B30.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Test Technique Code
Main Xmsn Gearbox	3000	2400 + 10,400*	Type I & II Flt. Test + Dynamic Systems Test	1
Main Xmsn Controls	3200	2400* 10,400	Type I & II Flt. Test* + Dynamic Systems Test	6&7
Main Xmsn Hub		2400 + 10,400	Type I & II Flt. Test + Dynamic Systems Test	
Intermediate Box	10,000	2400 + 10,400	Type I & II Flt. Test + Dynamic Systems Test	
Tail Rotor Xmsn	3700	2400 + 10,400	Type I & II Flt. Test + Dynamic Systems Test	
Main Rotor Blades	10,000	2400 + 10,400	Type I & II Flt. Test + Dynamic Systems Test	
Tail Rotor Blades	10,000	2400 + 10,400	Type I & II Flt. Test + Dynamic Systems Test	
Tail Drive Shaft	7600	2400 + 10,400	Type I & II Flt. Test + Dynamic Systems Test	
Tail Rotor Hub	10100	2400 + 10,400	Type I & II Flt. Test + Dynamic Systems Test	

TEST PROGRAM SCHEDULES AND COSTS

Test Code	Test Hours	Schedules Lead Time Mo	Schedules Oper Rate Hr/Mo	Schedules Elapsed Time/No. of Rigs	Schedules Total Time Mo	Costs Acq $/Rig	Costs Total Acq $K	Costs Oper $/Hr	Costs Oper Cost $K	Costs Total Cost $K
1	10,400	20	200	52.0 / 1	72.0	2000K	2000	580	6032	8032
2		18	400			1300K		280		
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5		6	500			100K		40		
6	900		70					2500	2250	2250
7	1500		20					NC		NC
Total Problem Identification Test Cost										10,282

*Test technique and hours associated with Code No.

Figure 95. Trade-Off Study Worksheet for Problem Identification Test Program No. 6B30.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Test Technique Code
Main Xmsn Gearbox	5200	6000 + 16,000*	Type I & II Flt. Test + Dynamic Systems Test*	1
Main Xmsn Controls	8100	6000* + 16,000	Type I & II Flt. Test* + Dynamic Systems Test	6&7
Main Xmsn Hub		6000 + 16,000	Type I & II Flt. Test + Dynamic Systems Test	
Intermediate Box	10,000	6000 + 16,000	Type I & II Flt. Test + Dynamic Systems Test	
Tail Rotor Xmsn	10,750	6000 + 16,000	Type I & II Flt. Test + Dynamic Systems Test	
Main Rotor Blades	10,000	6000 + 16,000	Type I & II Flt. Test + Dynamic Systems Test	
Tail Rotor Blades	10,000	60000 + 16,000	Type I & II Flt. Test + Dynamic Systems Test	
Tail Drive Shaft	10,000	6000 + 16,000	Type I & II Flt. Test + Dynamic Systems Test	
Tail Rotor Hub	10,000	6000 + 16,000	Type I & II Flt. Test + Dynamic Systems Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1	16,000	20	200	16.0 / 5	36.0	2000K	10,000	580	9280	19,280
2		18	400			1300K		280		
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5		6	500			100K		40		
6	4500		70					2500	11,250	11,250
7	1500		20					NC		NC
Total Problem Identification Test Cost										30,530

*Test technique and hours associated with Code No.

Figure 96. Trade-Off Study Worksheet for Problem Identification Test Program No. 3B52.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique	
			Name	Code
Main Xmsn Gearbox	5200	5600 + 16,800*	Type I & II Flt Test + Dynamic Systems Test*	1
Main Xmsn Controls	7900	5600* + 16,800	Type I & II Flt Test*+ Dynamic Systems Test	6&7
Main Xmsn Hub		5600 + 16,800	Type I & II Flt Test + Dynamic Systems Test	
Intermediate Box	10,000	5600 + 16,800	Type I & II Flt Test + Dynamic Systems Test	
Tail Rotor Xmsn	12,200	5600 + 16,800	Type I & II Flt Test + Dynamic Systems Test	
Main Rotor Blades	10,000	5600 + 16,800	Type I & II Flt Test + Dynamic Systems Test	
Tail Rotor Blades	10,000	5600 + 16,800	Type I & II Flt Test + Dynamic Systems Test	
Tail Drive Shaft	10,000	5600 + 16,800	Type I & II Flt Test + Dynamic Systems Test	
Tail Rotor Hub	10,000	5600 + 16,800	Type I & II Flt Test + Dynamic Systems Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1	16,800	20	200	28.0/3	48.0	2000K	6000	580	9744	15,744
2		18	400			1300K		280		
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5		6	500			100K		40		
6	4100		70					2500	10,250	10,250
7	1500		20					NC		NC
Total Problem Identification Test Cost										25,994

*Test technique and hours associated with Code No.

Figure 97. Trade-Off Study Worksheet for Problem Identification Test Program No. 4B52.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Test Technique Code
Main Xmsn Gearbox	5200	5300 + 17,700*	Type I & II Flt Test + Dynamic Systems Test*	1
Main Xmsn Controls	6250	5300* + 17,700	Type I & II Flt Test*+ Dynamic Systems Test	6&7
Main Xmsn Hub		5300 + 17,700	Type I & II Flt Test + Dynamic Systems Test	
Intermediate Box	10,000	5300 + 17,700	Type I & II Flt Test + Dynamic Systems Test	
Tail Rotor Xmsn	9900	5300 + 17,700	Type I & II Flt Test + Dynamic Systems Test	
Main Rotor Blades	10,000	5300 + 17,700	Type I & II Flt Test + Dynamic Systems Test	
Tail Rotor Blades	10,000	5300 + 17,700	Type I & II Flt Test + Dynamic Systems Test	
Tail Drive Shaft	10,000	5300 + 17,700	Type I & II Flt Test + Dynamic Systems Test	
Tail Rotor Hub	10,000	5300 + 17,700	Type I & II Flt Test + Dynamic Systems Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1	17,700	20	200	44.2/2	64.2	2000K	4000	580	10,266	14,266
2		18	400			1300K		280		
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5		6	500			100K		40		
6	3800		70					2500	9500	9500
7	1500		20					NC		NC
Total Problem Identification Test Cost										23,766

*Test technique and hours associated with Code No.

Figure 98. Trade-Off Study Worksheet for Problem Identification Test Program No. 6B52.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Test Technique Code
Main Xmsn Gearbox	600	1500 + 2000*	Type I Flight Test + Type II Flight Test*	6
Main Xmsn Controls	980	1500* + 2000	Type I Flight Test* + Type II Flight Test	7
Main Xmsn Hub		1500 + 2000	Type I Flight Test + Type II Flight Test	
Intermediate Box	2440	1500 + 2000	Type I Flight Test + Type II Flight Test	
Tail Rotor Xmsn	1040	1500 + 2000	Type I Flight Test + Type II Flight Test	
Main Rotor Blades	6060	1500 + 2000	Type I Flight Test + Type II Flight Test	
Tail Rotor Blades	10,000	1500 + 2000	Type I Flight Test + Type II Flight Test	
Tail Drive Shaft	2300	1500 + 2000	Type I Flight Test + Type II Flight Test	
Tail Rotor Hub	3200	1500 + 2000	Type I Flight Test + Type II Flight Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1		20	200			2000K		580		
2		18	400			1300K		280		
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5		6	500			100K		40		
6	2000		70					2500	5000	5000
7	1500		20					NC		NC
Total Problem Identification Test Cost										5000

*Test technique and hours associated with Code No.

Figure 99. Trade-Off Study Worksheet for Problem Identification Test Programs No. 3C6, 4C6, and 6C6.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Code
Main Xmsn Gearbox	3000	1500 + 9000*	Type I Flight Test + Type II Flight Test*	6
Main Xmsn Controls	5465	1500* + 9000	Type I Flight Test + Type II Flight Test	7
Main Xmsn Hub		1500 + 9000	Type I Flight Test + Type II Flight Test	
Intermediate Box	10,000	1500 + 9000	Type I Flight Test + Type II Flight Test	
Tail Rotor Xmsn	8060	1500 + 9000	Type I Flight Test + Type II Flight Test	
Main Rotor Blades	11,600	1500 + 9000	Type I Flight Test + Type II Flight Test	
Tail Rotor Blades	10,000	1500 + 9000	Type I Flight Test + Type II Flight Test	
Tail Drive Shaft	14,900	1500 + 9000	Type I Flight Test + Type II Flight Test	
Tail Rotor Hub	10,500	1500 + 9000	Type I Flight Test + Type II Flight Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1		20	200			2000K		580		
2		18	400			1300K		280		
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5		6	500			100K		40		
6	9000		70					2500	22500	22,500
7	1500		20					NC		NC
Total Problem Identification Test Cost										22,500

*Test technique and hours associated with Code No.

Figure 100. Trade-Off Study Worksheet for Problem Identification Test Programs No. 3C30, 4C30, and 6C30.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Test Technique Code
Main Xmsn Gearbox	5200	1500 + 14,000*	Type I Flight Test + Type II Flight Test*	6
Main Xmsn Controls	8800	1500* + 14,000	Type I Flight Test* + Type II Flight Test	7
Main Xmsn Hub		1500 + 14,000	Type I Flight Test Type II Flight Test	
Intermediate Box	10,000	1500 + 14,000	Type I Flight Test + Type II Flight Test	
Tail Rotor Xmsn	11,900	1500 + 14,000	Type I Flight Test + Type II Flight Test	
Main Rotor Blades	10,000	1500 + 14,000	Type I Flight Test + Type II Flight Test	
Tail Rotor Blades	10,000	1500 + 14,000	Type I Flight Test + Type II Flight Test	
Tail Drive Shaft	10,000	1500 + 14,000	Type I Flight Test + Type II Flight Test	
Tail Rotor Hub	10,000	1500 + 14,000	Type I Flight Test + Type II Flight Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1		20	200			2000K		580		
2		18	400			1300K		280		
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5		6	500			100K		40		
6	14,000		70					2500	35000	35, 000
7	1500		20					NC		NC
Total Problem Identification Test Cost										35,000

*Test technique and hours associated with Code No.

Figure 101. Trade-Off Study Worksheet for Problem Identification Test Programs No. 3C52, 4C52, and 6C52.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique	
			Name	Code
Main Xmsn Gearbox	600	3500*	Closed Loop*	2
Main Xmsn Controls	600	1250 + 2450*	Whirl Tower + Swashplate Bench*	5
Main Xmsn Hub		1250*	Whirl Tower*	3
Intermediate Box	1850	1300*	Tail Rotor Stand*	4
Tail Rotor Xmsn	620	1300	Tail Rotor Stand	
Main Rotor Blades	600	1250	Whirl Tower	
Tail Rotor Blades	1650	1300	Tail Rotor Stand	
Tail Drive Shaft	600	1300	Tail Rotor Stand	
Tail Rotor Hub	1800	1300	Tail Rotor Stand	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1		20	200			2000K		580		
2	3500	18	400	8.8/1	26.8	1300K	1300	280	980	2280
3	1250	20	350	3.6/1	23.6	560K 2600K	560	220	275	835
4	1300	16	400	3.3/1	19.3	330K	330	110	143	473
5	2450	6	500	4.9/1	10.9	100K	100	40	98	198
6			70					2500		
7			20					NC		NC
Total Problem Identification Test Cost										3,786

*Test technique and hours associated with Code No.

Figure 102. Trade-Off Study Worksheet for Problem Identification Test Programs No. 3D6, 4D6, and 6D6.

TEST PROGRAM COMPONENT RELIABILITY

<table>
<tr><th rowspan="2">Component</th><th rowspan="2">MTBR Out</th><th rowspan="2">Test Hours</th><th colspan="2">Test Technique</th></tr>
<tr><th>Name</th><th>Code</th></tr>
<tr><td>Main Xmsn Gearbox</td><td>3000</td><td>10,500*</td><td>Closed Loop*</td><td>2</td></tr>
<tr><td>Main Xmsn Controls</td><td rowspan="2">3000</td><td>6500 + 4,000*</td><td>Whirl Tower + Swashplate Bench*</td><td>5</td></tr>
<tr><td>Main Xmsn Hub</td><td>6500*</td><td>Whirl Tower*</td><td>3</td></tr>
<tr><td>Intermediate Box</td><td>5000</td><td>5000*</td><td>Tail Rotor Stand*</td><td>4</td></tr>
<tr><td>Tail Rotor Xmsn</td><td>3000</td><td>5000</td><td>Tail Rotor Stand</td><td></td></tr>
<tr><td>Main Rotor Blades</td><td>5300</td><td>6500</td><td>Whirl Tower</td><td></td></tr>
<tr><td>Tail Rotor Blades</td><td>8000</td><td>5000</td><td>Tail Rotor Stand</td><td></td></tr>
<tr><td>Tail Drive Shaft</td><td>5200</td><td>5000</td><td>Tail Rotor Stand</td><td></td></tr>
<tr><td>Tail Rotor Hub</td><td>7700</td><td>5000</td><td>Tail Rotor Stand</td><td></td></tr>
</table>

TEST PROGRAM SCHEDULES AND COSTS

<table>
<tr><th colspan="2">Test</th><th colspan="4">Schedules</th><th colspan="5">Costs</th></tr>
<tr><th>Code</th><th>Hours</th><th>Lead Time Mo</th><th>Oper Rate Hr/Mo</th><th>Elapsed Time/No. of Rigs</th><th>Total Time Mo</th><th>Acq $/Rig</th><th>Total Acq $K</th><th>Oper $/Hr</th><th>Oper Cost $K</th><th>Total Cost $K</th></tr>
<tr><td>1</td><td></td><td>20</td><td>200</td><td></td><td></td><td>2000K</td><td></td><td>580</td><td></td><td></td></tr>
<tr><td>2</td><td>10,500</td><td>18</td><td>400</td><td>13.2/2</td><td>31.2</td><td>1300K</td><td>2600</td><td>280</td><td>2940</td><td>5540</td></tr>
<tr><td>3</td><td>6500</td><td>20</td><td>350</td><td>9.3/2</td><td>29.3</td><td>560K
2600K</td><td>1120</td><td>220</td><td>1430</td><td>2550</td></tr>
<tr><td>4</td><td>5000</td><td>16</td><td>400</td><td>12.5/1</td><td>28.5</td><td>330K</td><td>330</td><td>110</td><td>550</td><td>880</td></tr>
<tr><td>5</td><td>4000</td><td>6</td><td>500</td><td>8/1</td><td>14.1</td><td>100K</td><td>100</td><td>40</td><td>160</td><td>260</td></tr>
<tr><td>6</td><td></td><td></td><td>70</td><td></td><td></td><td></td><td></td><td>2500</td><td></td><td></td></tr>
<tr><td>7</td><td></td><td></td><td>20</td><td></td><td></td><td></td><td></td><td>NC</td><td></td><td>NC</td></tr>
<tr><td colspan="10">Total Problem Identification Test Cost</td><td>9,230</td></tr>
</table>

*Test technique and hours associated with Code No.

Figure 103. Trade-Off Study Worksheet for Problem Identification Test Program No. 3D30.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique	
			Name	Code
Main Xmsn Gearbox	3000	10,500*	Closed Loop*	2
Main Xmsn Controls	3000	6500 + 4000*	Whirl Tower + Swashplate Bench*	5
Main Xmsn Hub		6500*	Whirl Tower*	3
Intermediate Box	5000	5000	Tail Rotor Stand*	4
Tail Rotor Xmsn	3000	5000	Tail Rotor Stand	
Main Rotor Blades	5300	6500	Whirl Tower	
Tail Rotor Blades	8000	5000	Tail Rotor Stand	
Tail Drive Shaft	5200	5000	Tail Rotor Stand	
Tail Rotor Hub	7700	5000	Tail Rotor Stand	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1		20	200			2000K		580		
2	10,500	18	400	26.3/1	44.3	1300K	1300	280	2940	4240
3	6500	20	350	18.6/1	38.6	560K 2600K	560	220	1430	1990
4	5000	16	400	12.5/1	28.5	330K	330	110	550	880
5	4000	6	500	8/1	14.0	100K	100	40	160	260
6			70					2500		
7			20					NC		NC
Total Problem Identification Test Cost										7,370

*Test technique and hours associated with Code No.

Figure 104. Trade-Off Study Worksheet for Problem Identification Test Programs No. 4D30 and 6D30.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Test Technique Code
Main Xmsn Gearbox	5200	15,500*	Closed Loop*	2
Main Xmsn Controls	5200	9000 + 500*	Whirl Tower + Swashplate Bench*	5
Main Xmsn Hub		9000*	Whirl Tower*	3
Intermediate Box	7400	7000*	Tail Rotor Stand*	4
Tail Rotor Xmsn	5200	7000	Whirl Tower	
Main Rotor Blades	7000	9000	Tail Rotor Stand	
Tail Rotor Blades	9000	7000	Tail Rotor Stand	
Tail Drive Shaft	9000	7000	Tail Rotor Stand	
Tail Rotor Hub	9000	7000	Tail Rotor Stand	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1		20	200			2000K		580		
2	15,500	18	400	13.0/3	31.0	1300K	3900	280	4340	8240
3	9000	20	350	12.8/2	32.8	560K 2600K	1120	220	1980	3100
4	7000	16	400	17.5/1	33.5	330K	330	110	770	1100
5	500	6	500	1/1	7	100K	100	40	20	120
6			70					2500		
7			20					NC		NC
Total Problem Identification Test Cost										12,560

*Test technique and hours associated with Code No.

Figure 105. Trade-Off Study Worksheet for Problem Identification Test Program No. 3D52.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Test Technique Code
Main Xmsn Gearbox	5200	15,500*	Closed Loop*	2
Main Xmsn Controls	5200	9000+ 500*	Whirl Tower + Swashplate Bench*	5
Main Xmsn Hub		9000*	Whirl Tower*	3
Intermediate Box	7400	7000*	Tail Rotor Stand*	4
Tail Rotor Xmsn	5200	7000	Tail Rotor Stand	
Main Rotor Blades	7000	9000	Whirl Tower	
Tail Rotor Blades	9000	7000	Tail Rotor Stand	
Tail Drive Shaft	9000	7000	Tail Rotor Stand	
Tail Rotor Hub	9000	7000	Tail Rotor Sta d	

TEST PROGRAM SCHEDULES AND COSTS

Test Code	Test Hours	Schedules Lead Time Mo	Schedules Oper Rate Hr/Mo	Schedules Elapsed Time/No. of Rigs	Schedules Total Time Mo	Costs Acq $/Rig	Costs Total Acq $K	Costs Oper $/Hr	Costs Oper Cost $K	Costs Total Cost $K
1		20	200			2000K		580		
2	15,500	18	400	19.4 / 2	37.4	1300K	2600	280	4340	6940
3	9000	20	350	25.7 / 1	45.7	560K 2600K	560	220	1980	3100
4	7000	16	400	17.5 / 1	33.5	330K	330	110	770	1100
5	500	6	500	1 / 1	7	100K	100	40	20	120
6			70					2500		
7			20					NC		NC
Total Problem Identification Test Cost										11,260

*Test technique and hours associated with Code No.

Figure 106. Trade-Off Study Worksheet for Problem Identification Test Program No. 4D52.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique	
			Name	Code
Main Xmsn Gearbox	5200	15,500*	Closed Loop*	2
Main Xmsn Controls	5200	9000 + 500*	Whirl Tower + Swashplate Bench	5
Main Xmsn Hub		9000*	Whirl Tower*	3
Intermediate Box	7400	7000*	Tail Rotor Stand*	4
Tail Rotor Xmsn	5200	7000	Tail Rotor Stand	
Main Rotor Blades	7000	9000	Whirl Tower	
Tail Rotor Blades	9000	7000	Tail Rotor Stand	
Tail Drive Shaft	9000	7000	Tail Rotor Stand	
Tail Rotor Hub	9000	7000	Tail Rotor Stand	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1		20	200			2000K		580		
2	15500	18	400	38.8/1	56.8	1300K	1300	280	4340	5640
3	9000	20	350	25.7/1	45.7	560K 2600K	560	220	1980	3100
4	7000	16	400	17.5/1	33.5	330K	330	110	770	1100
5	500	6	500	1/1	7.0	100K	100	40	20	120
6			70					2500		
7			20					NC		NC
Total Problem Identification Test Cost										9,960

*Test technique and hours associated with Code No.

Figure 107. Trade-Off Study Worksheet for Problem Identification Test Program No. 6D52.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique	
			Name	Code
Main Xmsn Gearbox	600	3500*	Dynamic Systems Test*	1
Main Xmsn Controls	634	3500	Dynamic Systems Test	
Main Xmsn Hub		3500	Dynamic Systems Test	
Intermediate Box	2700	3500	Dynamic Systems Test	
Tail Rotor Xmsn	1320	3500	Dynamic Systems Test	
Main Rotor Blades	2900	3500	Dynamic Systems Test	
Tail Rotor Blades	8300	3500	Dynamic Systems Test	
Tail Drive Shaft	2500	3500	Dynamic Systems Test	
Tail Rotor Hub	5200	3500	Dynamic Systems Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1	3500	20	200	9 / 2	29	2000K	4000	580	2030	6030
2		[illegible]8	400			1300K		280		
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5		6	500			100K		40		
6			70					2500		
7			20					NC		NC
Total Problem Identification Test Cost										6,030

*Test technique and hours associated with Code No.

Figure 108. Trade-Off Study Worksheet for Problem Identification Test Program No. 3E6.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Test Technique Code
Main Xmsn Gearbox	600	3500*	Dynamic Systems Test*	1
Main Xmsn Controls	634	3500	Dynamic Systems Test	
Main Xmsn Hub		3500	Dynamic Systems Test	
Intermediate Box	2700	3500	Dynamic Systems Test	
Tail Rotor Xmsn	1320	3500	Dynamic Systems Test	
Main Rotor Blades	2900	3500	Dynamic Systems Test	
Tail Rotor Blades	8300	3500	Dynamic Systems Test	
Tail Drive Shaft	2500	3500	Dynamic Systems Test	
Tail Rotor Hub	5200	3500	Dynamic Systems Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1	3500	20	200	17.1 / 1	37.5	2000K	2000	580	2030	4,030
2		18	400			1300K		280		
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5		6	500			100K		40		
6			70					2500		
7			20					NC		NC
Total Problem Identification Test Cost										4,030

*Test technique and hours associated with Code No.

Figure 109. Trade-Off Study Worksheet for Problem Identification Test Programs No. 4E6 and 6E6.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Test Technique Code
Main Xmsn Gearbox	3000	10,500*	Dynamic Systems Test*	1
Main Xmsn Controls	6500	10,500	Dynamic Systems Test	
Main Xmsn Hub		10,500	Dynamic Systems Test	
Intermediate Box	10,000	10,500	Dynamic Systems Test	
Tail Rotor Xmsn	10,000	10,500	Dynamic Systems Test	
Main Rotor Blades	7800	10,500	Dynamic Systems Test	
Tail Rotor Blades	10,000	10,500	Dynamic Systems Test	
Tail Drive Shaft	9000	10,500	Dynamic Systems Test	
Tail Rotor Hub	9000	10,500	Dynamic Systems Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1	10,500	20	200	12.8 / 4	32.8	2000K	8000	580	6090	14,090
2		18	400			1300K		280		
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5		6	500			100K		40		
6			70					2500		
7			20					NC		NC
Total Problem Identification Test Cost										14,090

*Test technique and hours associated with Code No.

Figure 110. Trade-Off Study Worksheet for Problem Identification Test Program No. 3E30.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Test Technique Code
Main Xmsn Gearbox	3000	10,500*	Dynamic Systems Test*	1
Main Xmsn Controls	6500	10,500	Dynamic Systems Test	
Main Xmsn Hub		10,500	Dynamic Systems Test	
Intermediate Box	10,000	10,500	Dynamic Systems Test	
Tail Rotor Xmsn	10,000	10,500	Dynamic Systems Test	
Main Rotor Blades	7800	10,500	Dynamic Systems Test	
Tail Rotor Blades	10,000	10,500	Dynamic Systems Test	
Tail Drive Shaft	9000	10,500	Dynamic Systems Test	
Tail Rotor Hub	9000	10,500	Dynamic Systems Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1	10,500	20	200	26.3 / 2	46.3	2000K	4000	580	6090	10,090
2		18	400			1300K		280		
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5		6	500			100K		40		
6			70					2500		
7			20					NC		NC
Total Problem Identification Test Cost										10,090

*Test technique and hours associated with Code No.

Figure 111. Trade-Off Study Worksheet for Problem Identification Test Program No. 4E30.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Code
Main Xmsn Gearbox	3000	10,500*	Dynamic Systems Test*	1
Main Xmsn Controls	6500	10,500	Dynamic Systems Test	
Main Xmsn Hub		10,500	Dynamic Systems Test	
Intermediate Box	10,000	10,500	Dynamic Systems Test	
Tail Rotor Xmsn	10,000	10,500	Dynamic Systems Test	
Main Rotor Blades	7800	10,500	Dynamic Systems Test	
Tail Rotor Blades	10,000	10,500	Dynamic Systems Test	
Tail Drive Shaft	9000	10,500	Dynamic Systems Test	
Tail Rotor Hub	9000	10,500	Dynamic Systems Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1	10,500	20	200	52.5 / 1	72.5	2000K	2000	580	6090	8090
2		18	400			1300K		280		
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5		6	500			100K		40		
6			70					2500		
7			20					NC		NC
Total Problem Identification Test Cost										8090

*Test technique and hours associated with Code No.

Figure 112. Trade-Off Study Worksheet for Problem Identification Test Program No. 6E30.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique	
			Name	Code
Main Xmsn Gearbox	5200	15,500*	Dynamic Systems Test*	1
Main Xmsn Controls	9500	15,500	Dynamic Systems Test	
Main Xmsn Hub		15,500	Dynamic Systems Test	
Intermediate Box	10,000	15,500	Dynamic Systems Test	
Tail Rotor Xmsn	10,000	15,500	Dynamic Systems Test	
Main Rotor Blades	10,000	15,500	Dynamic Systems Test	
Tail Rotor Blades	10,000	15,500	Dynamic Systems Test	
Tail Drive Shaft	10,000	15,500	Dynamic Systems Test	
Tail Rotor Hub	10,000	15,500	Dynamic Systems Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1	15,500	20	200	15.5 / 5	35.5	2000K	10,000	580	8990	18,990
2		18	400			1300K		280		
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5		6	500			100K		40		
6			70					2500		
7			20					NC		NC
Total Problem Identification Test Cost										1899.0

*Test technique and hours associated with Code No.

Figure 113. Trade-Off Study Worksheet for Problem Identification Test Program No. 3E52.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Code
Main Xmsn Gearbox	5200	15,500*	Dynamic Systems Test*	1
Main Xmsn Controls	8600	15,500	Dynamic Systems Test	
Main Xmsn Hub		15,500	Dynamic Systems Test	
Intermediate Box	10,000	15,500	Dynamic Systems Test	
Tail Rotor Xmsn	10,000	15,500	Dynamic Systems Test	
Main Rotor Blades	10,000	15,500	Dynamic Systems Test	
Tail Rotor Blades	10,000	15,500	Dynamic Systems Test	
Tail Drive Shaft	10,000	15,500	Dynamic Systems Test	
Tail Rotor Hub	10,000	15,500	Dynamic Systems Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1	15,500	20	200	25.8/3	45.8	2000K	6000	580	8990	14,990
2		18	400			1300K		280		
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5		6	500			100K		40		
6			70					2500		
7			20					NC		NC
Total Problem Identification Test Cost										14,990

*Test technique and hours associated with Code No.

Figure 114. Trade-Off Study Worksheet for Problem Identification Test Program No. 4E52.

TEST PROGRAM COMPONENT RELIABILITY

Component	MTBR Out	Test Hours	Test Technique Name	Code
Main Xmsn Gearbox	5200	15,500*	Dynamic Systems Test*	1
Main Xmsn Controls	8600	15,500	Dynamic Systems Test	
Main Xmsn Hub		15,500	Dynamic Systems Test	
Intermediate Box	10,000	15,500	Dynamic Systems Test	
Tail Rotor Xmsn	10,000	15,500	Dynamic Systems Test	
Main Rotor Blades	10,000	15,500	Dynamic Systems Test	
Tail Rotor Blades	10,000	15,500	Dynamic Systems Test	
Tail Drive Shaft	10,000	15,500	Dynamic Systems Test	
Tail Rotor Hub	10,000	15,500	Dynamic Systems Test	

TEST PROGRAM SCHEDULES AND COSTS

Test		Schedules				Costs				
Code	Hours	Lead Time Mo	Oper Rate Hr/Mo	Elapsed Time/No. of Rigs	Total Time Mo	Acq $/Rig	Total Acq $K	Oper $/Hr	Oper Cost $K	Total Cost $K
1	15,500	20	200	38.8 / 2	58.8	2000K	4000	580	8990	12,990
2		18	400			1300K		280		
3		20	350			560K 2600K		220		
4		16	400			330K		110		
5		6	500			100K		40		
6			70					2500		
7			20					NC		NC
Total Problem Identification Test Cost										12,990

*Test technique and hours associated with Code No.

Figure 115. Trade-Off Study Worksheet for Problem Identification Test Program No. 6E52.

APPENDIX V

RELIABILITY TEST COST TRADE-OFF STUDIES

This appendix consists of plots whose purpose is to determine the minimum cost combination of problem identification tests and demonstration tests. Each figure represents a specific MTBR* value and confidence level to be demonstrated for a specific demonstration philosophy and elapsed time. Some of the figures represent several elapsed time periods (and are noted where applicable). The minimum demonstration duration at which the specific MTBR* and confidence level can be demonstrated (zero failures) is indicated by a solid vertical line. Table XVII provides a summary of the data at the optimum cost points.

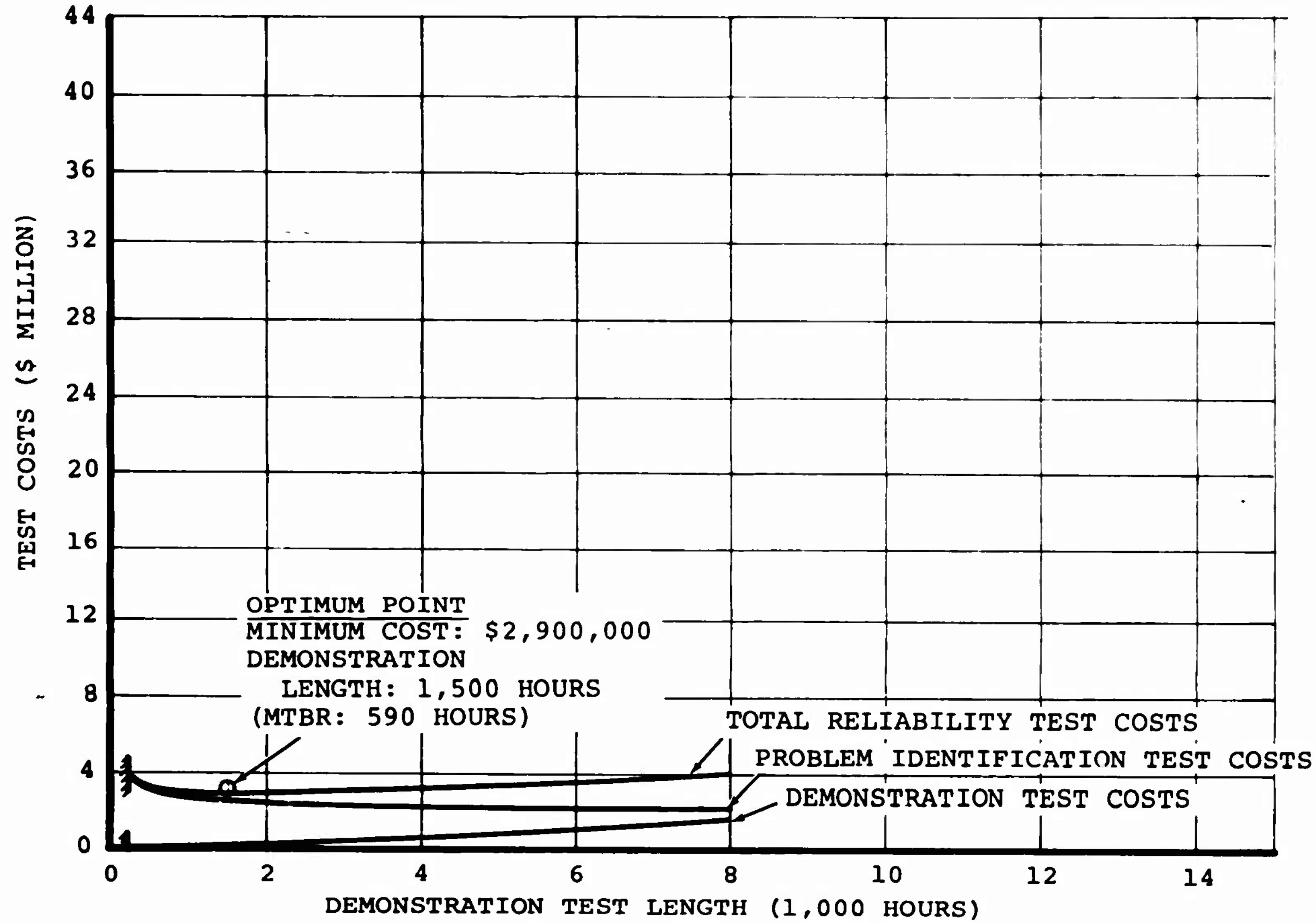


Figure 116. Total Reliability Test Costs Trade-Off Study for 500-Hour MTBR* at 30% Confidence, 80% Probability of Passing Demonstration, and 3-Year Demo-Out.

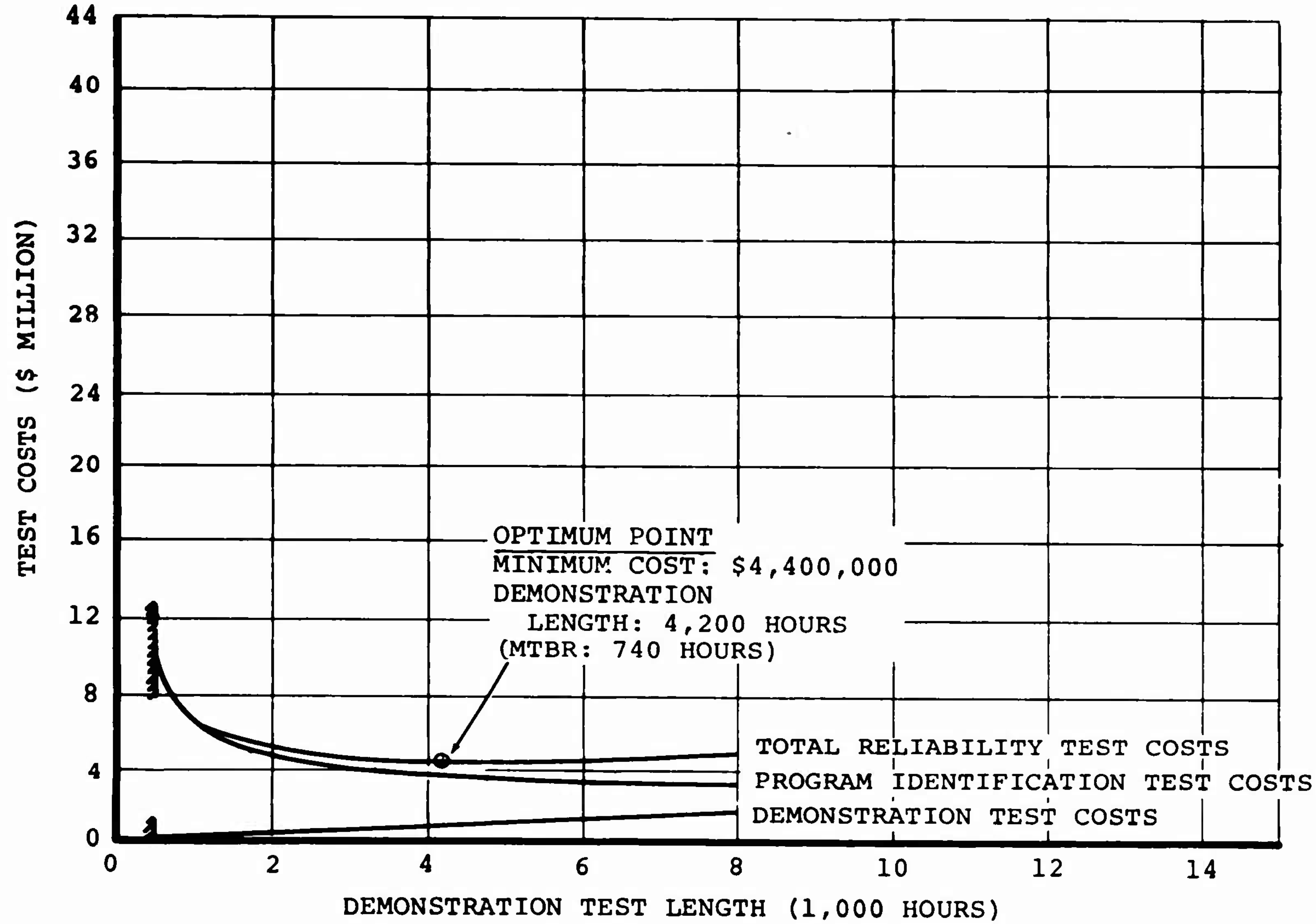


Figure 117. Total Reliability Test Costs Trade-Off Study for 500-Hour MTBR* at 60% Confidence, 80% Probability of Passing Demonstration, and 3-Year Demo-Out.

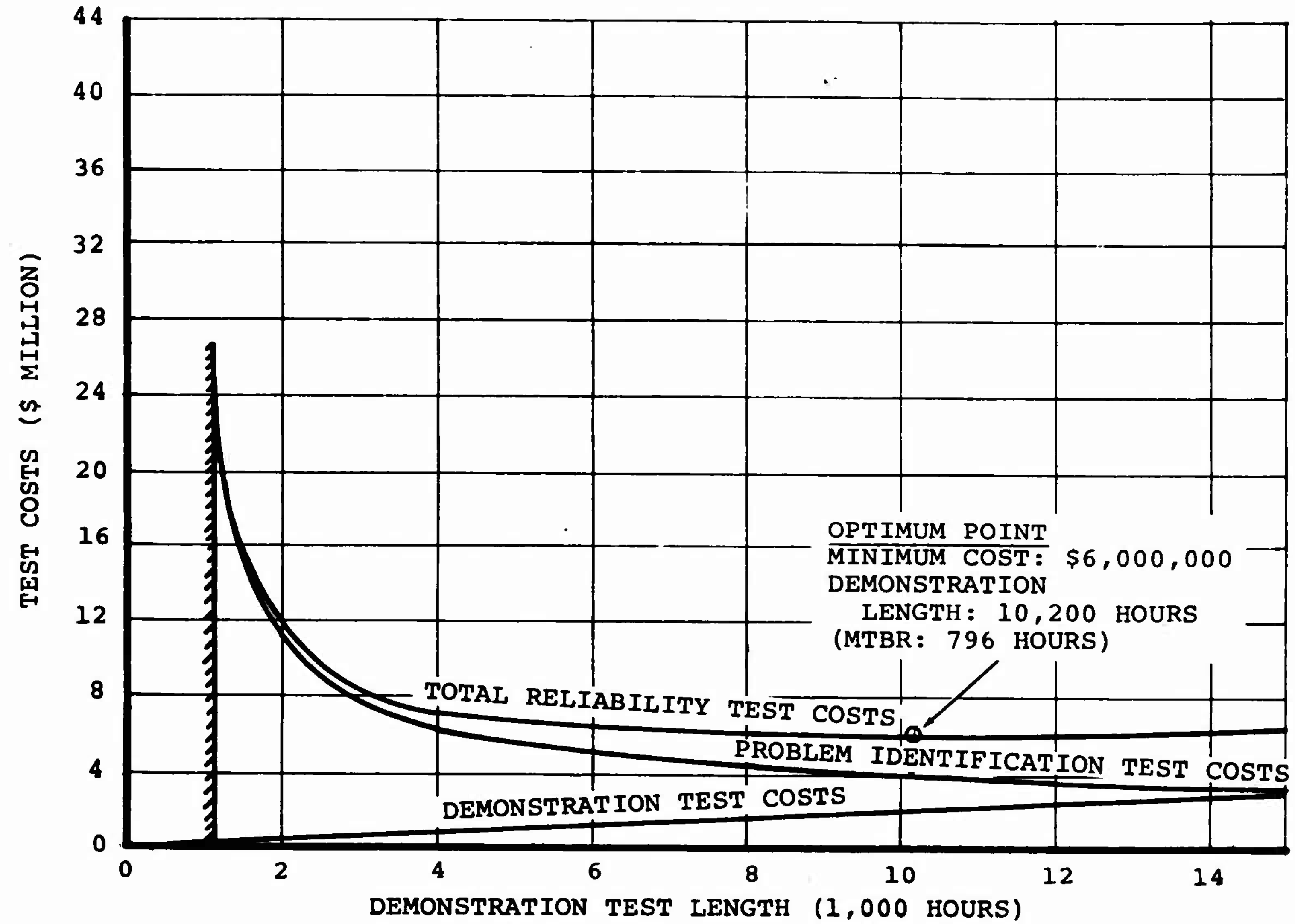


Figure 118. Total Reliability Test Costs Trade-Off Study for 500-Hour MTBR* at 90% Confidence, 80% Probability of Passing Demonstration, and 3-Year Demo-Out.

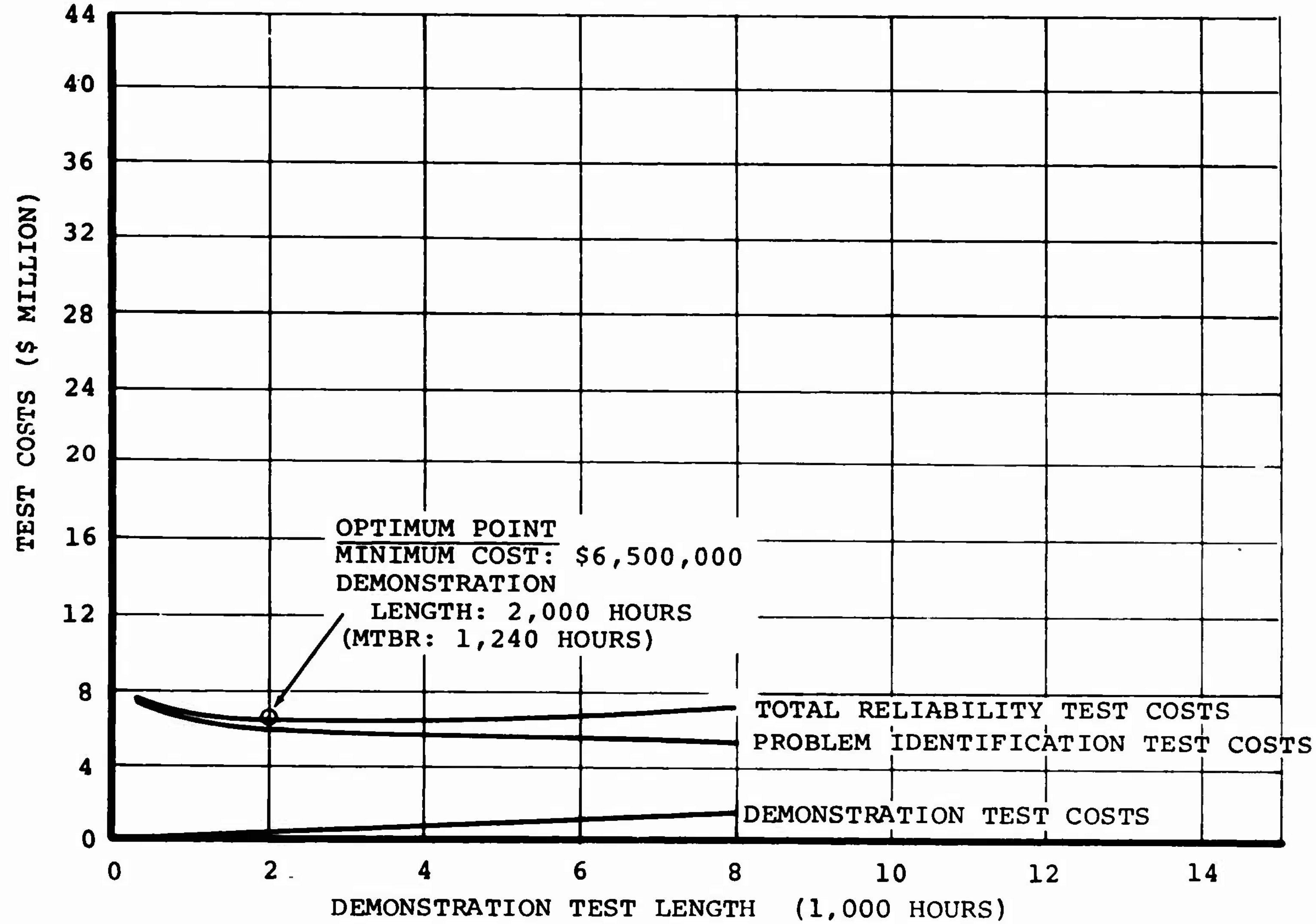


Figure 119. Total Reliability Test Costs Trade-Off Study for 1,000-Hour MTBR* at 30% Confidence, 80% Probability of Passing Demonstration, and 3-Year Demo-Out.

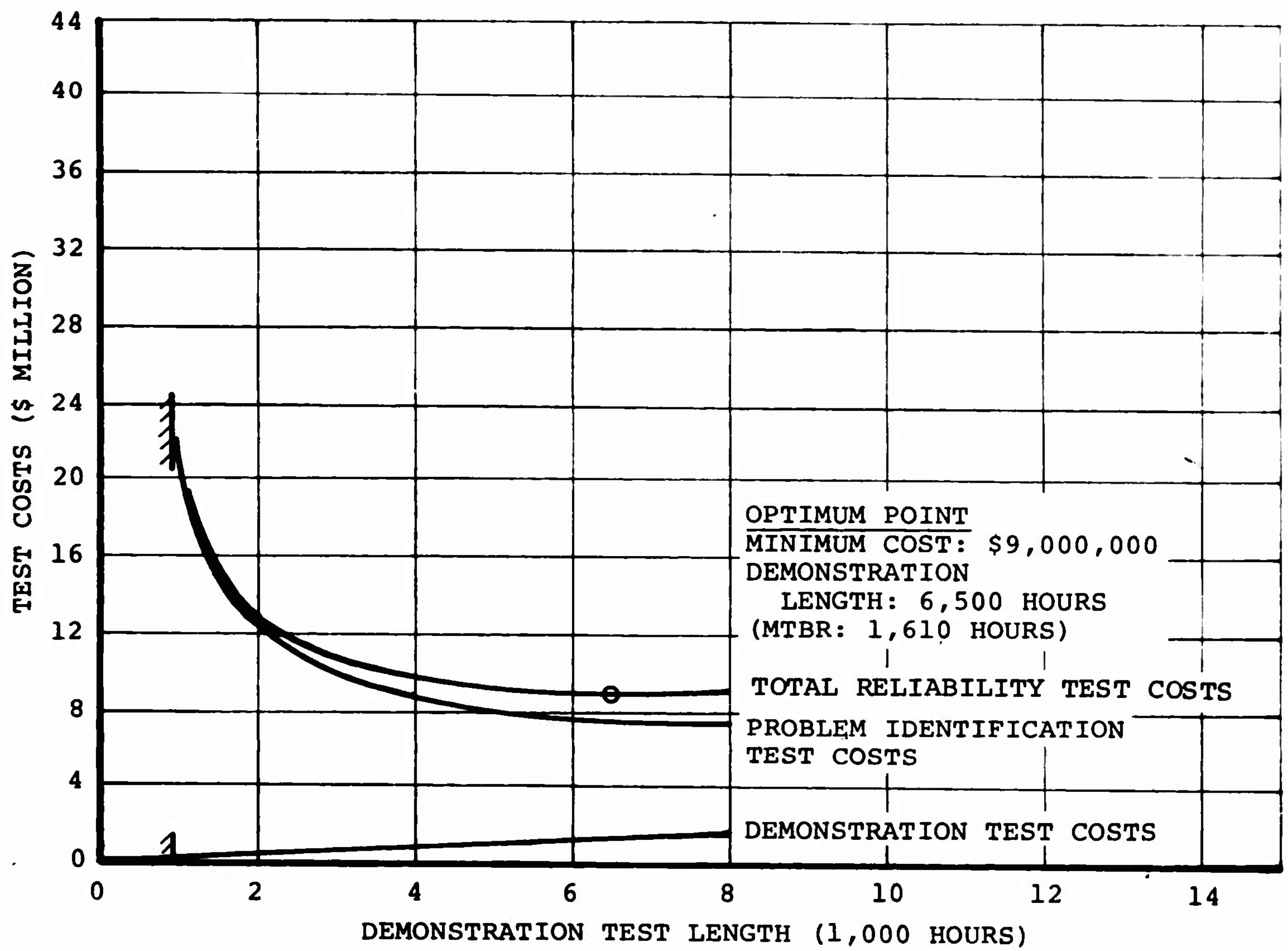


Figure 120. Total Reliability Test Costs Trade-Off Study for 1,000-Hour MTBR* at 60% Confidence, 80% Probability of Passing Demonstration, and 3-Year Demo-Out.

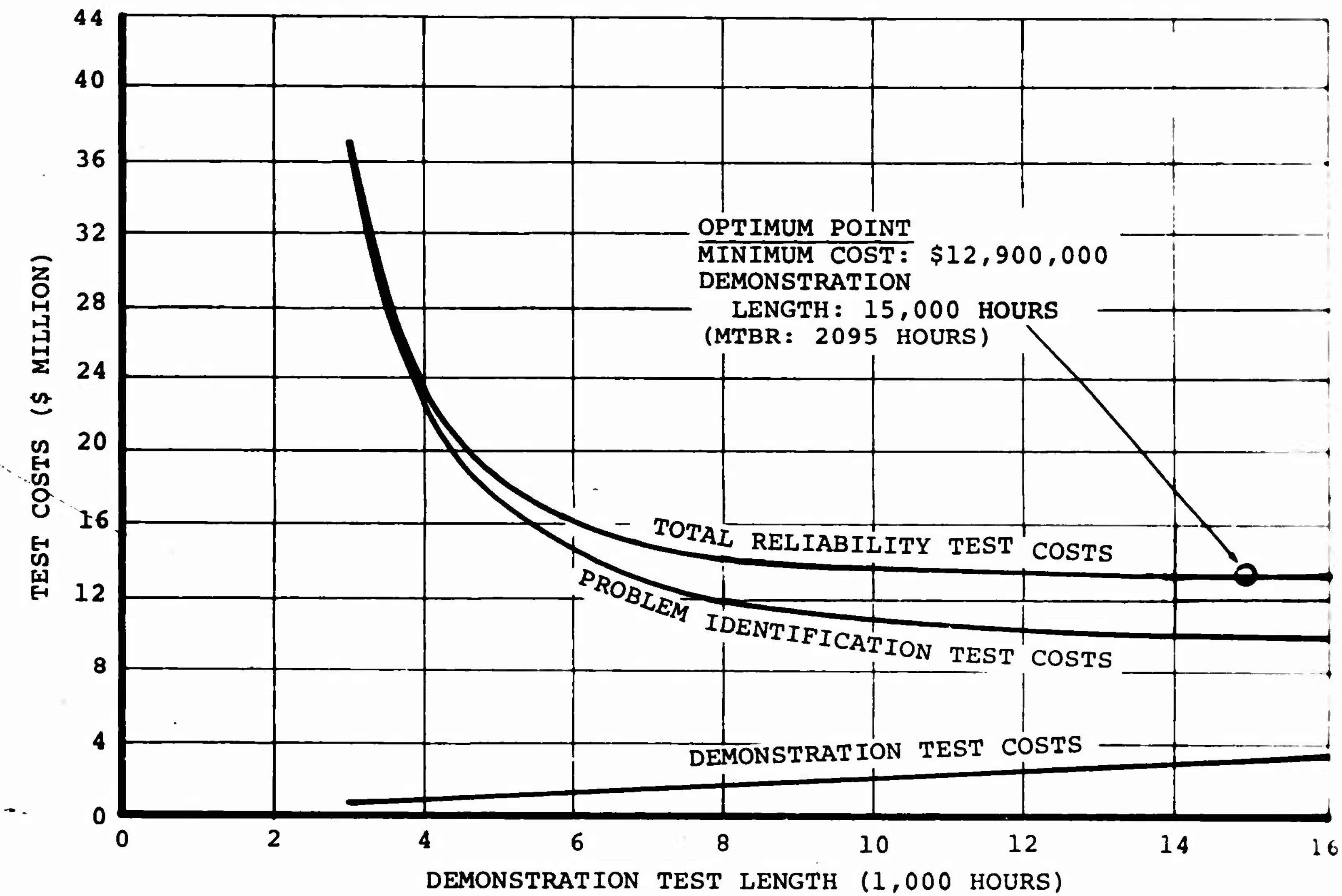


Figure 121. Total Reliability Test Costs Trade-Off Study for 1,000-Hour MTBR* at 90% Confidence, 80% Probability of Passing Demonstration, and 3-Year Demo-Out.

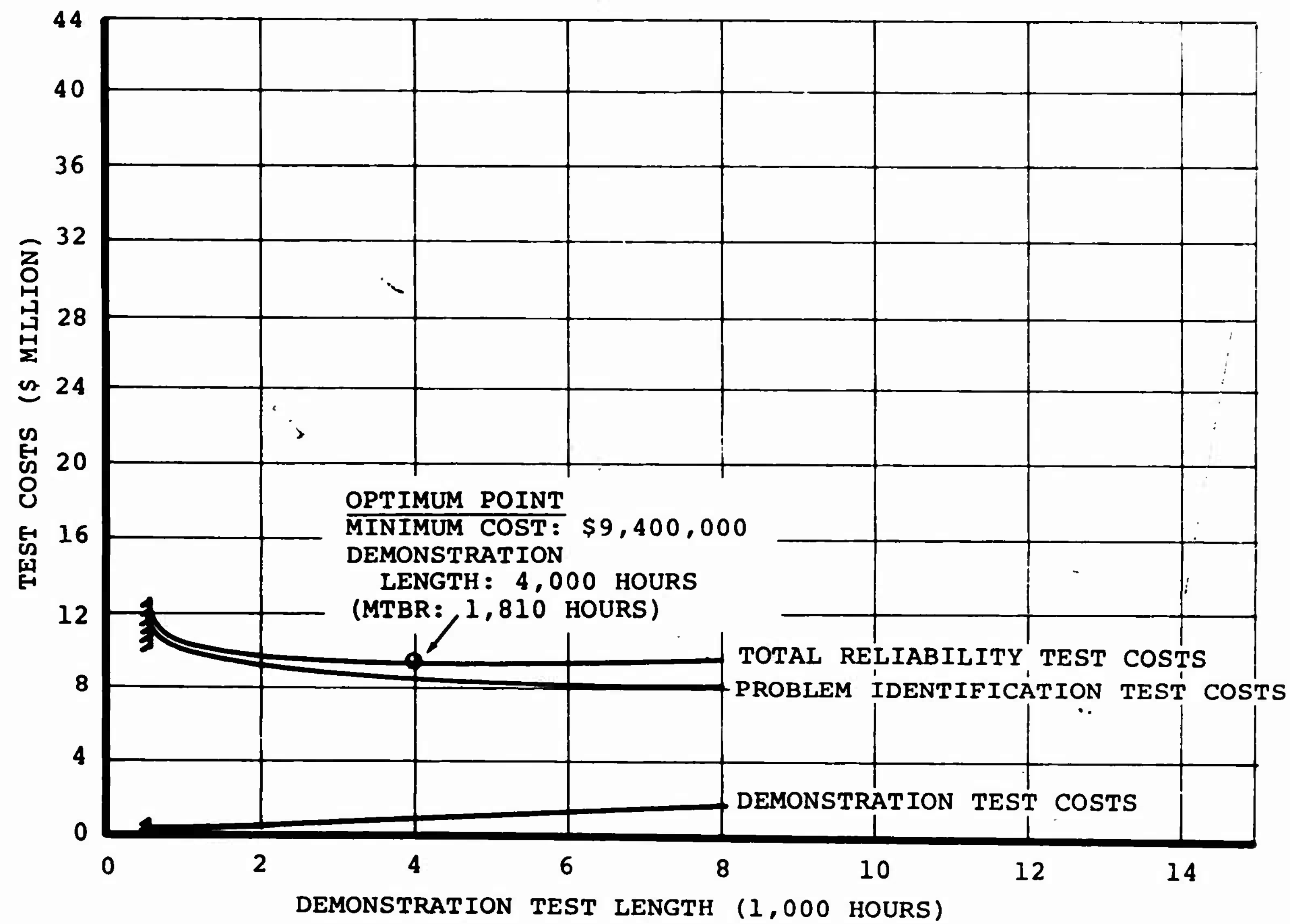


Figure 122. Total Reliability Test Costs Trade-Off Study for 1,500-Hour MTBR* at 30% Confidence, 80% Probability of Passing Demonstration, and 3-Year Demo-Out.

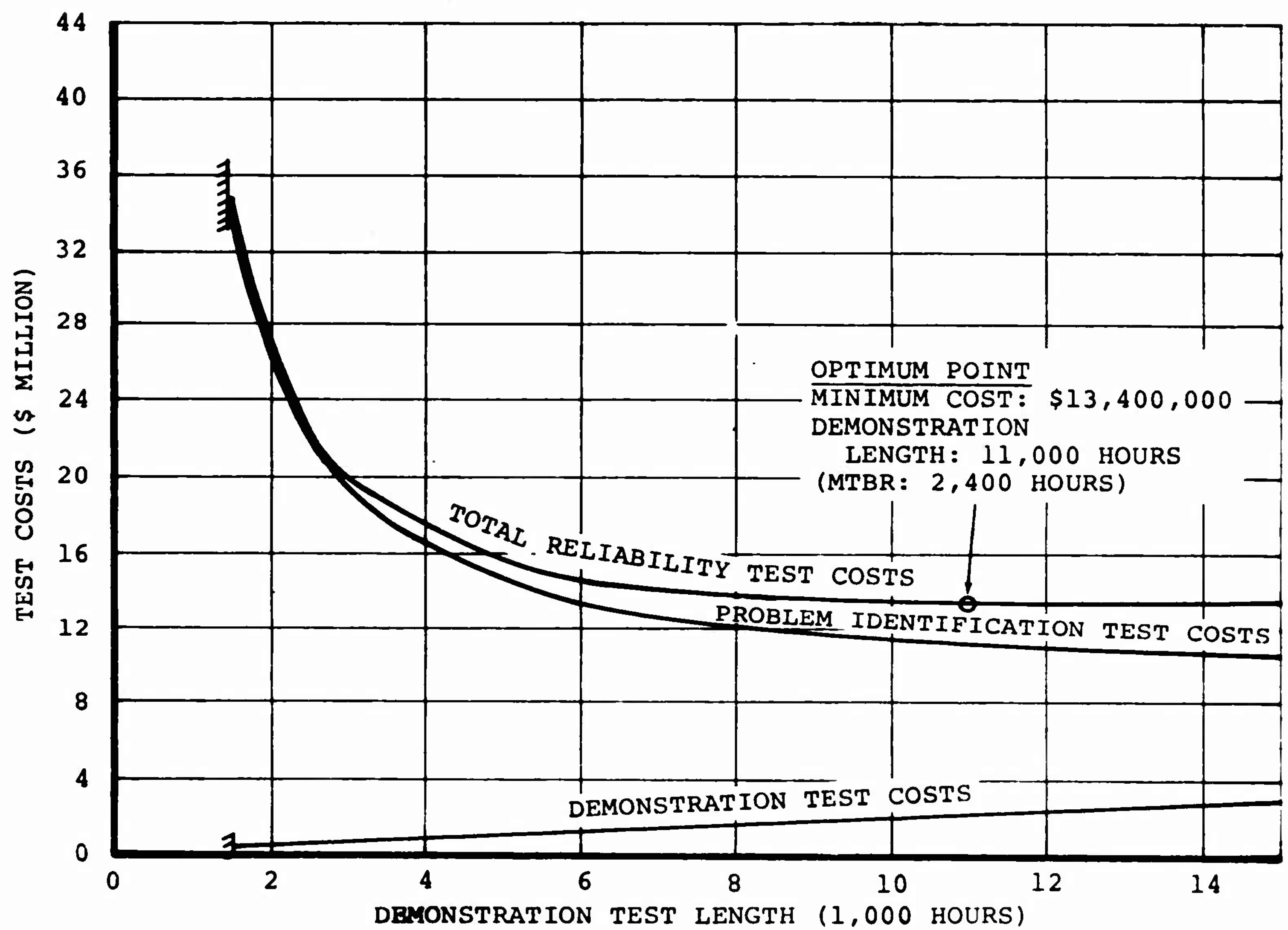


Figure 123. Total Reliability Test Costs Trade-Off Study for 1,500-Hour MTBR* at 60% Confidence, 80% Probability of Passing Demonstration, and 3-Year Demo-Out.

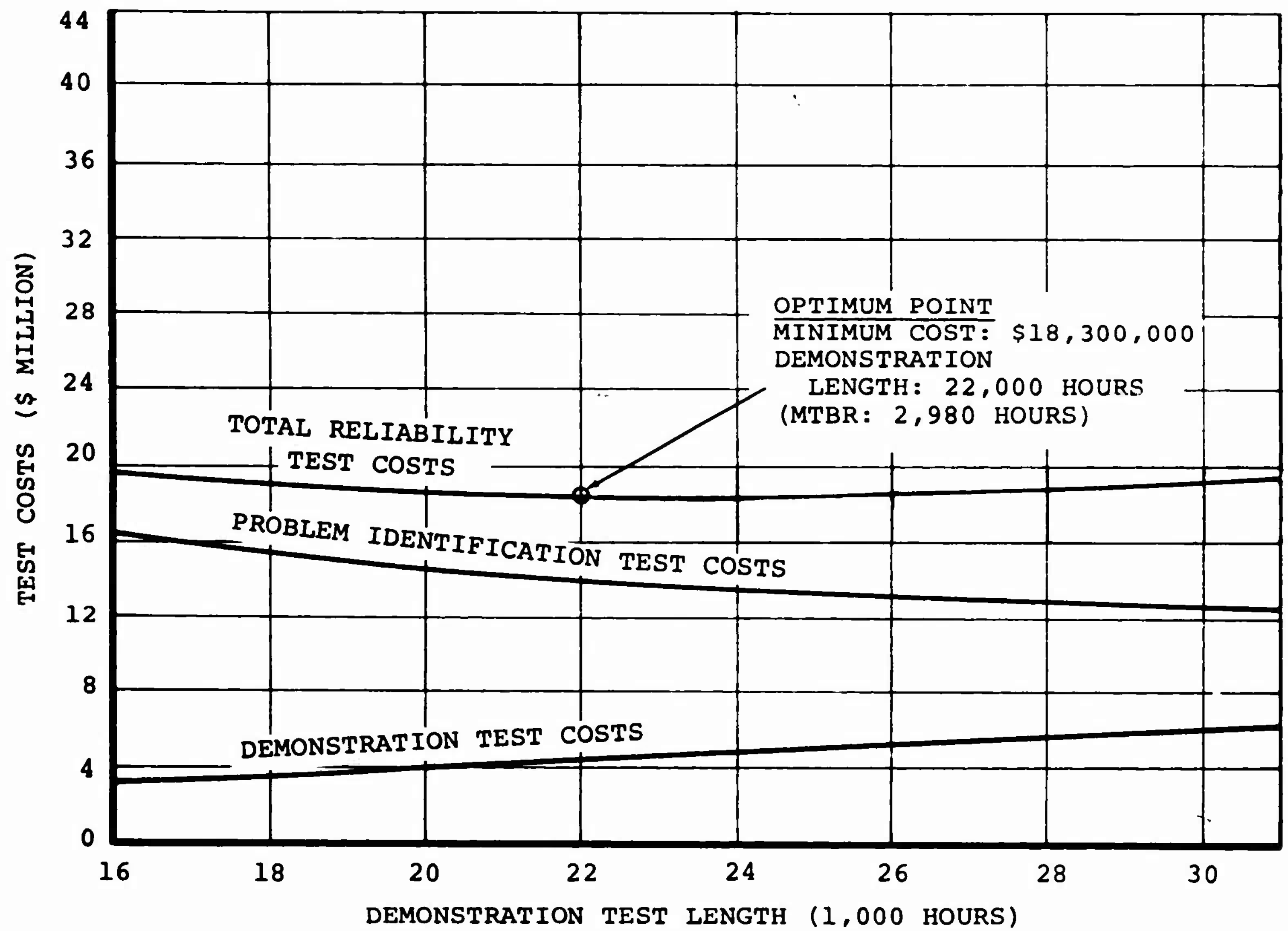


Figure 124. Total Reliability Test Costs Trade-Off Study for 1,500-Hour MTBR* at 90% Confidence, 80% Probability of Passing Demonstration, and 3-Year Demo-Out.

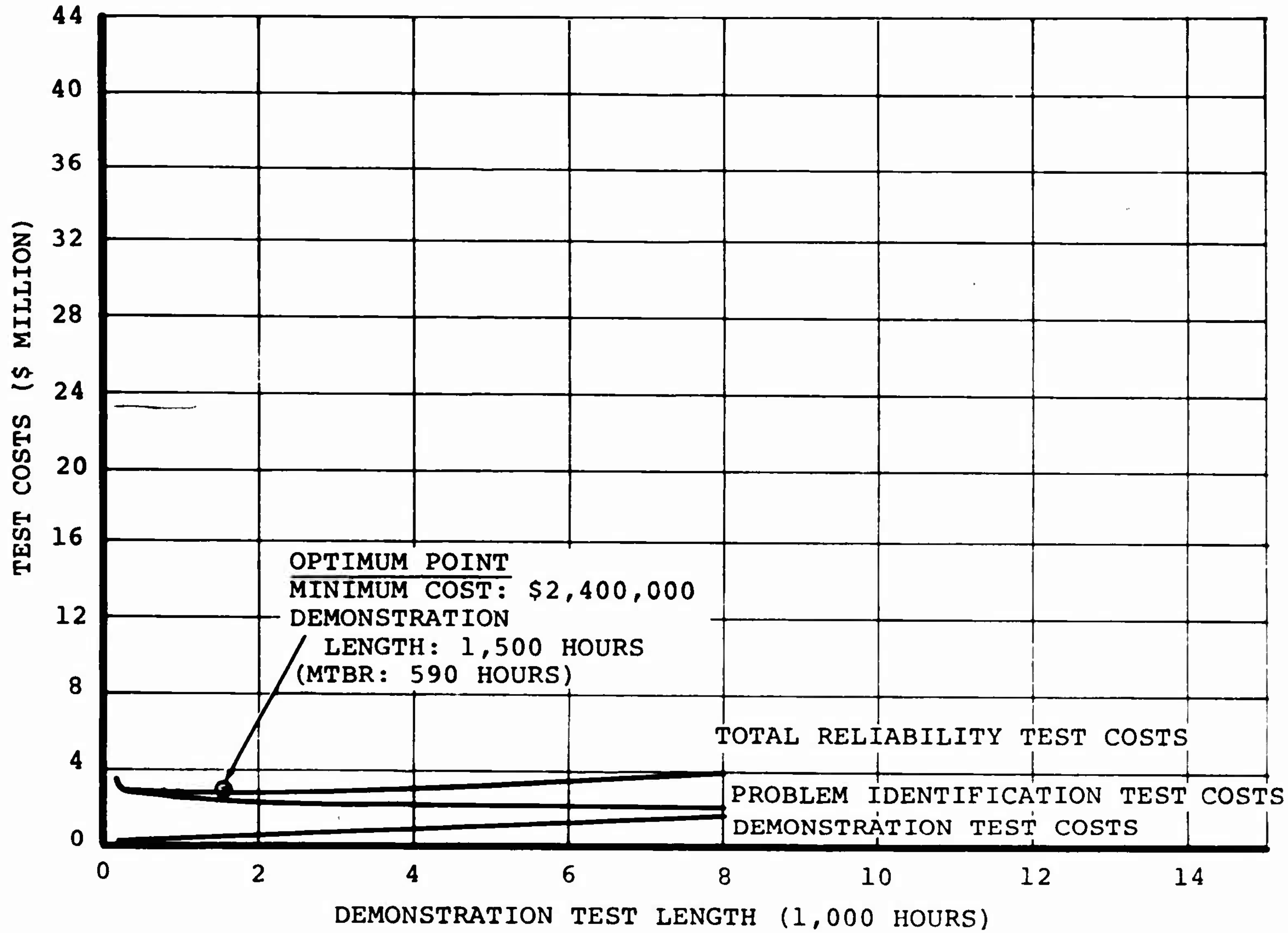


Figure 125. Total Reliability Test Costs Trade-Off Study for 500-Hour MTBR* at 30% Confidence, 80% Probability of Passing Demonstration, and 4- and 6-Year Demo-Out.

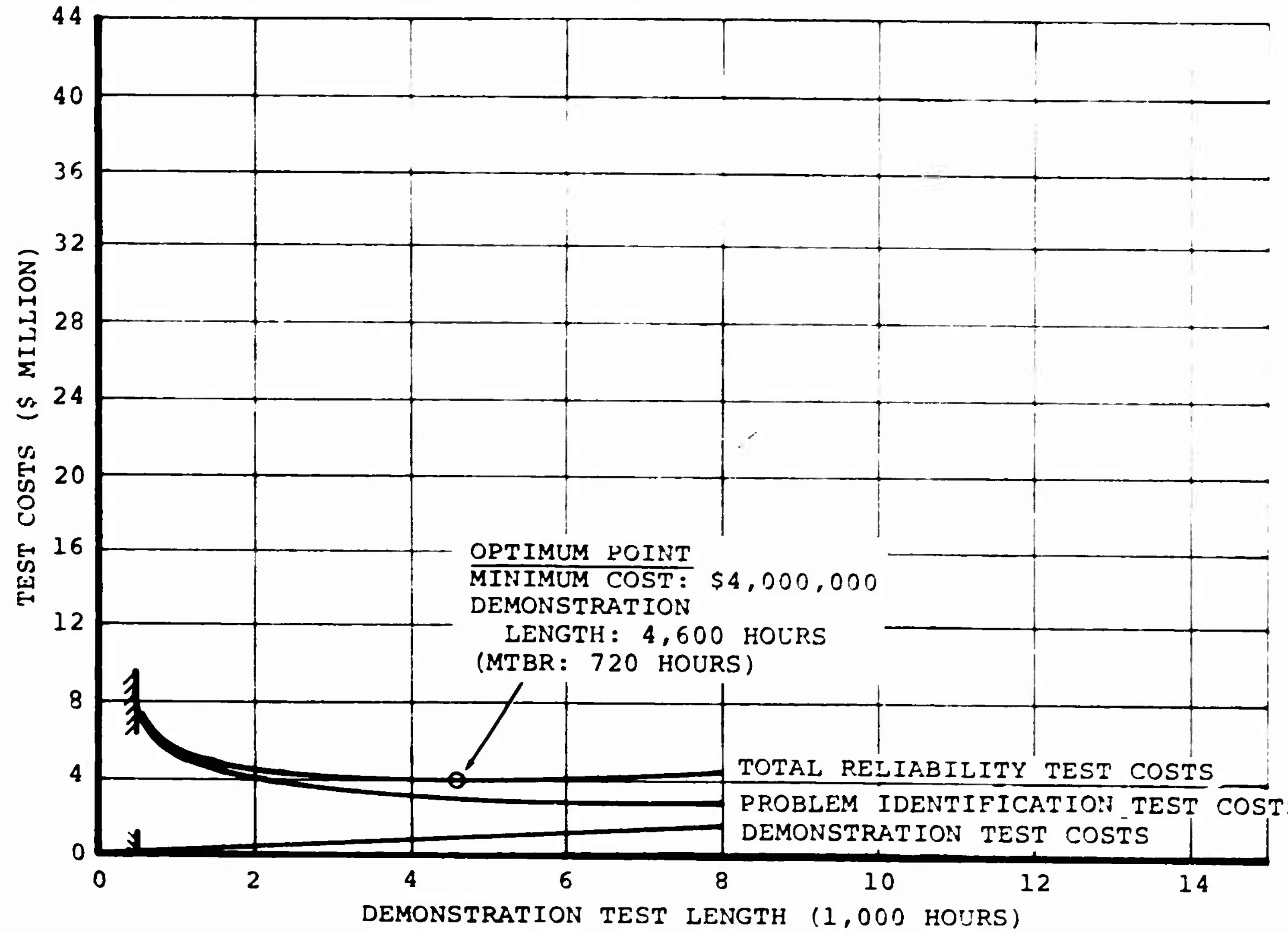


Figure 126. Total Reliability Test Costs Trade-Off Study for 500-Hour MTBR* at 60% Confidence, 80% Probability of Passing Demonstration, and 4- and 6-Year Demo-Out.

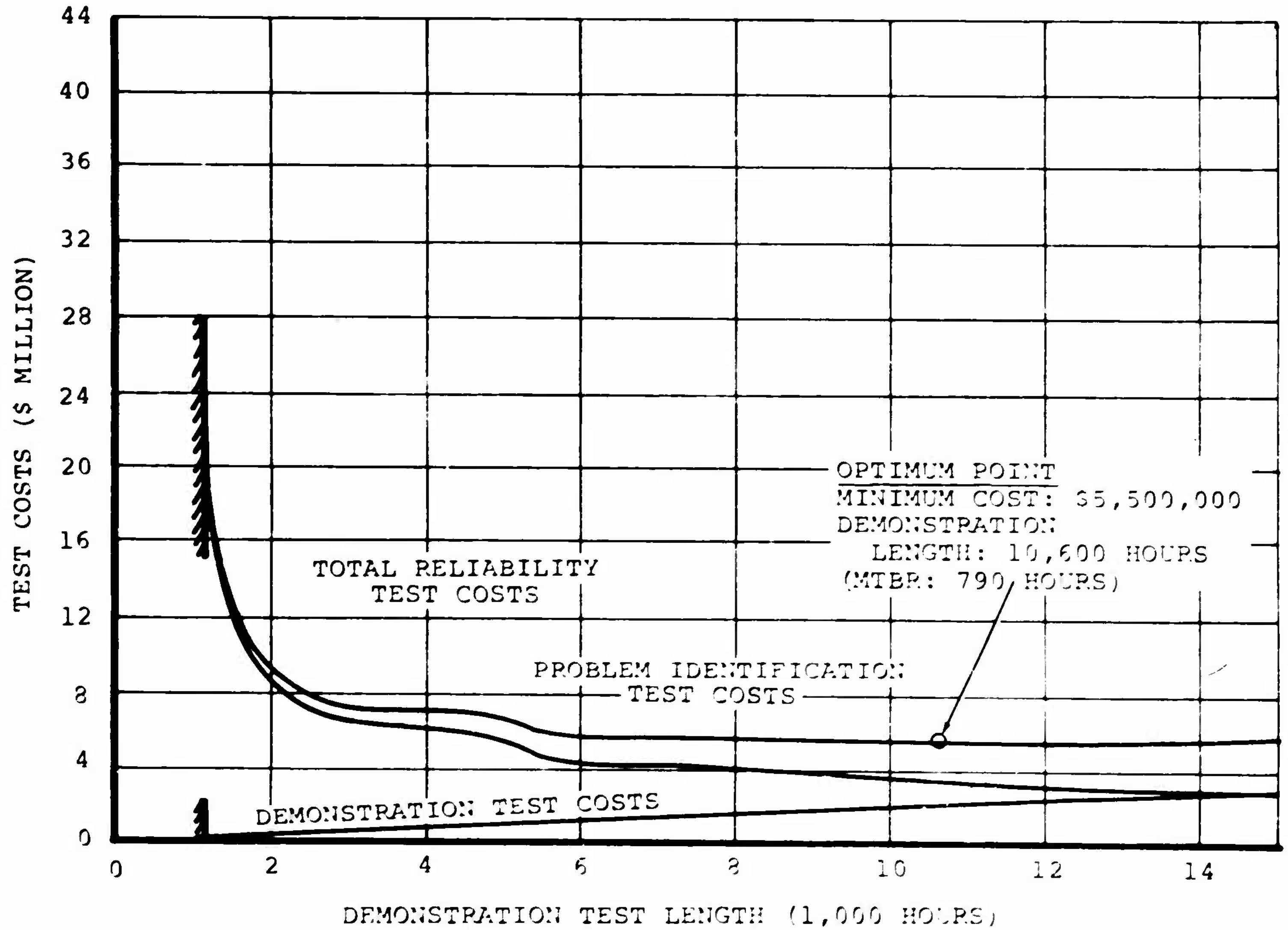


Figure 127. Total Reliability Test Costs Trade-Off Study for 500-Hour MTBR* at 90% Confidence, 80% Probability of Passing Demonstration, and 4-Year Demo-Out.

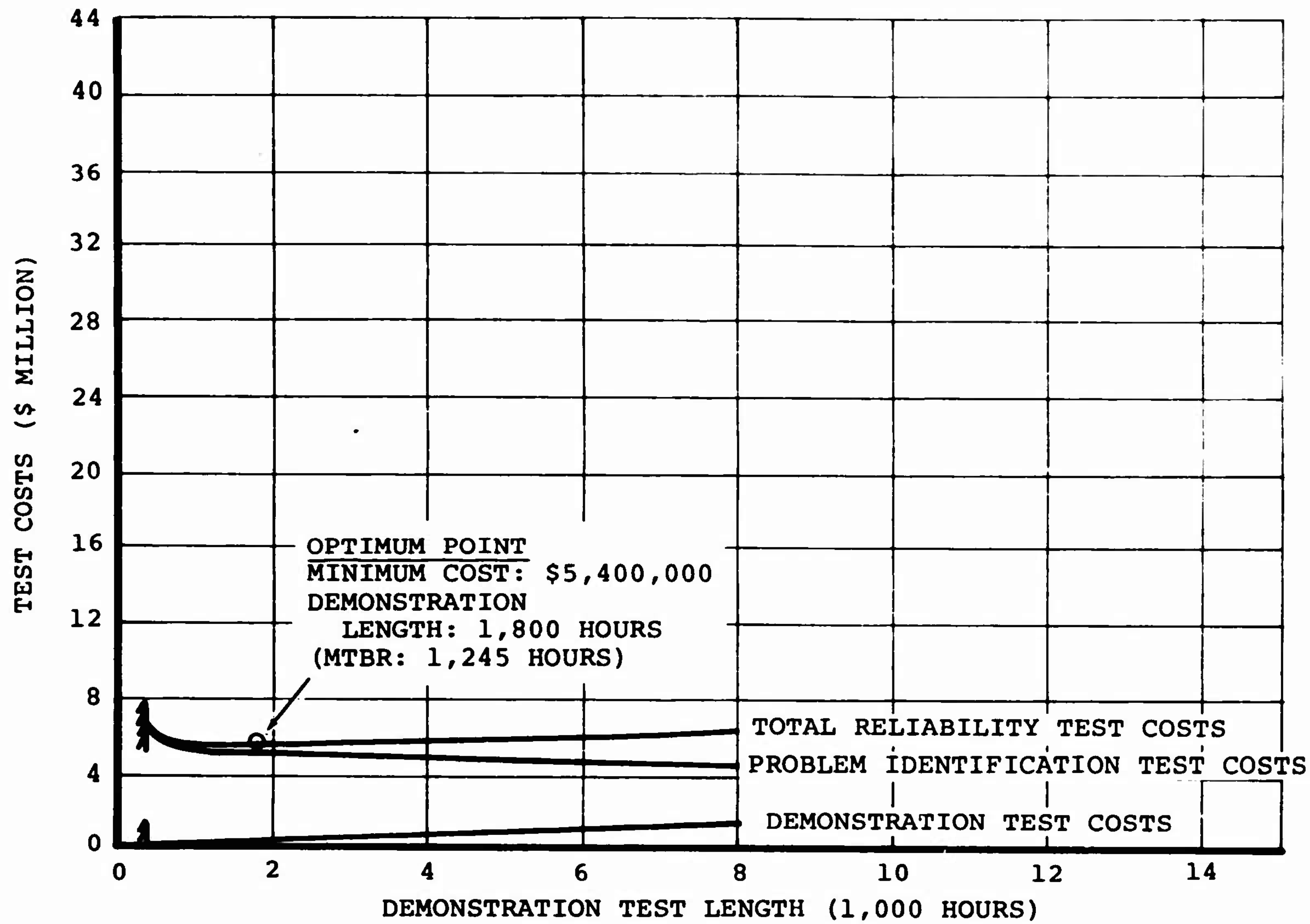


Figure 128. Total Reliability Test Costs Trade-Off Study for 1,000-Hour MTBR* at 30% Confidence, 80% Probability of Passing Demonstration, and 4- and 6-Year Demo-Out.

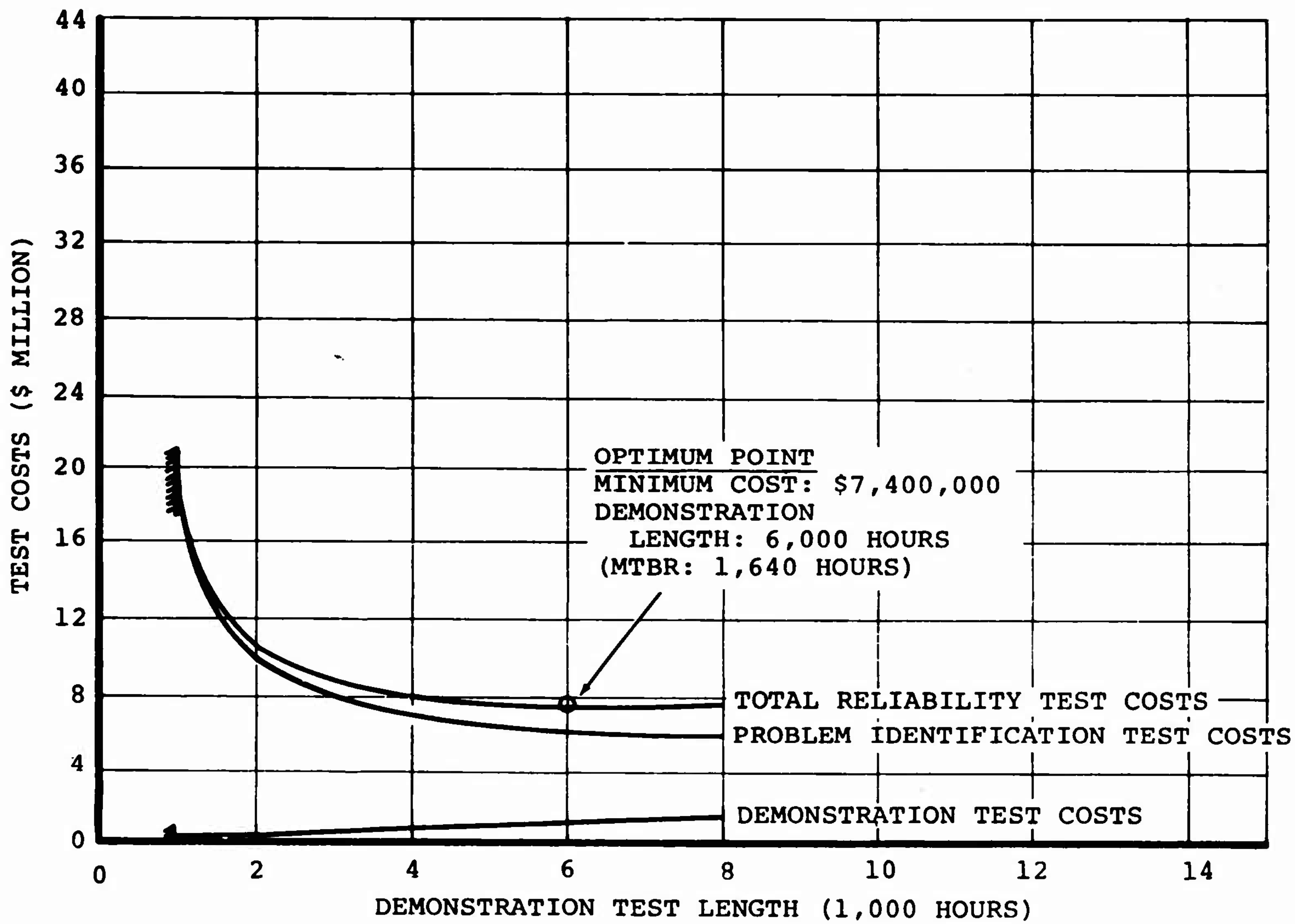


Figure 129. Total Reliability Test Costs Trade-Off Study for 1,000-Hour MTBR* at 60% Confidence, 80% Probability of Passing Demonstration, and 4-Year Demo-Out.

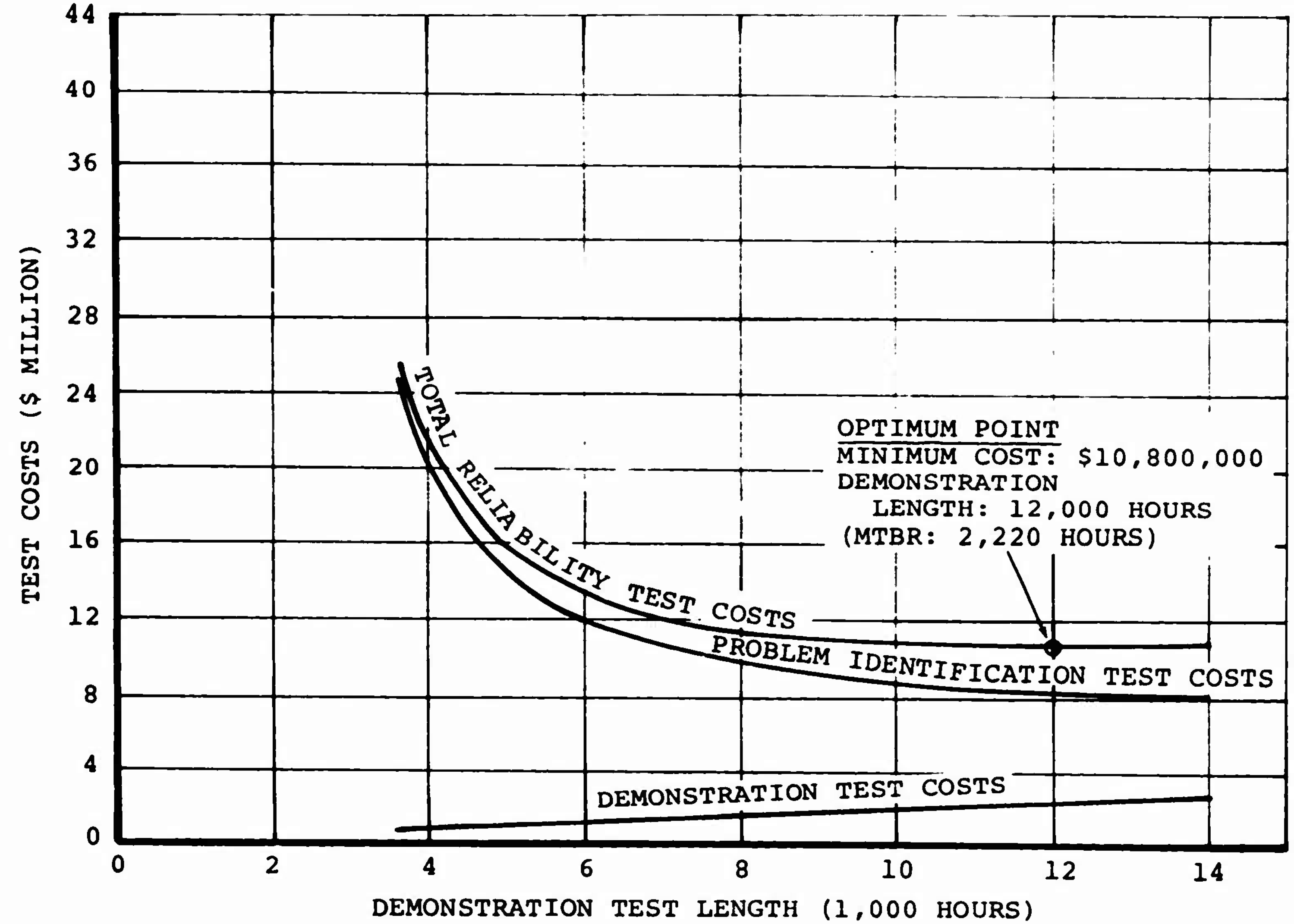


Figure 130. Total Reliability Test Costs Trade-Off Study for 1,000-Hour MTBR* at 90% Confidence, 80% Probability of Passing Demonstration, and 4-Year Demo-Out.

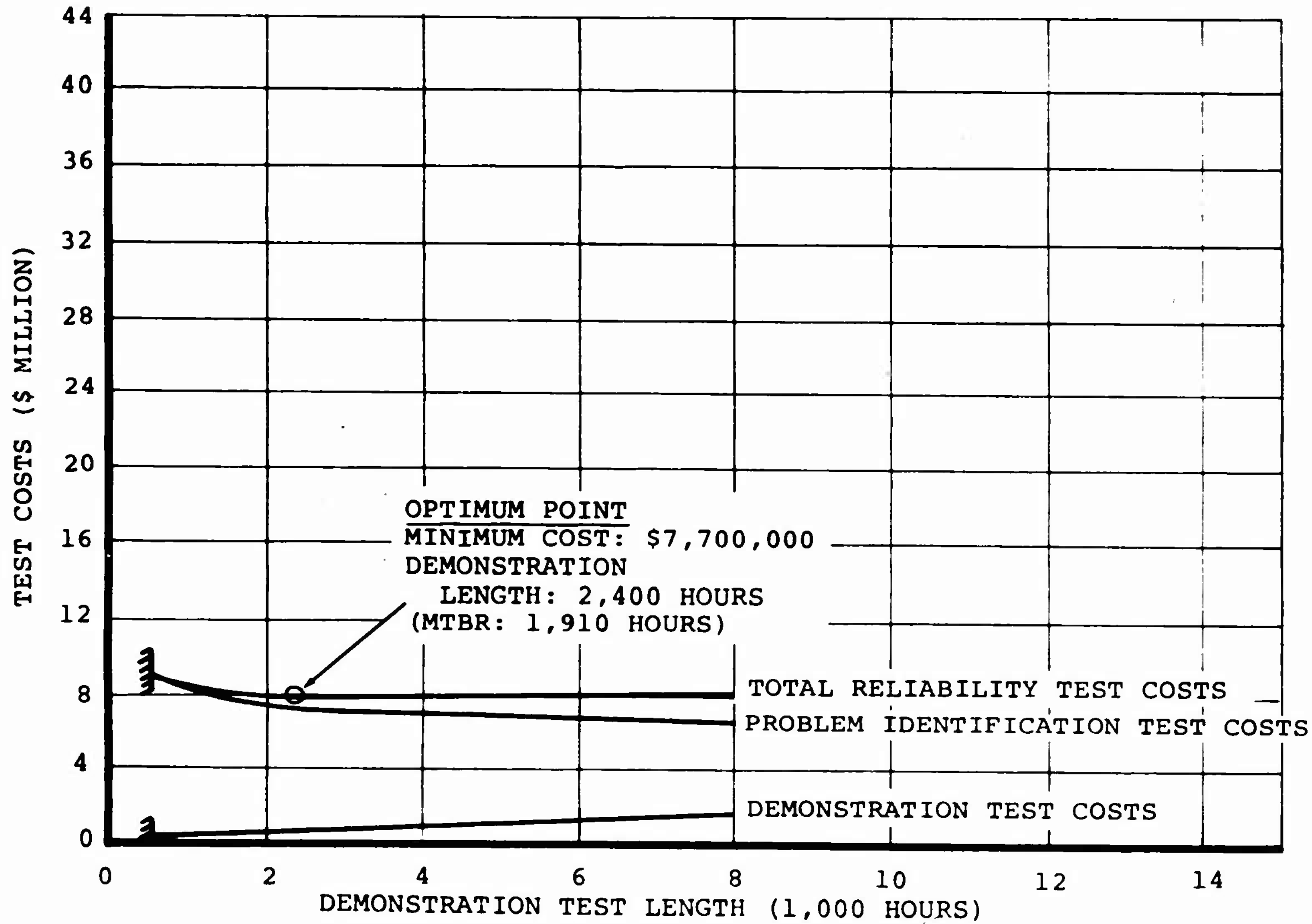


Figure 131. Total Reliability Test Costs Trade-Off Study for 1,500-Hour MTBR* at 30% Confidence, 80% Probability of Passing Demonstration, and 4-Year Demo-Out.

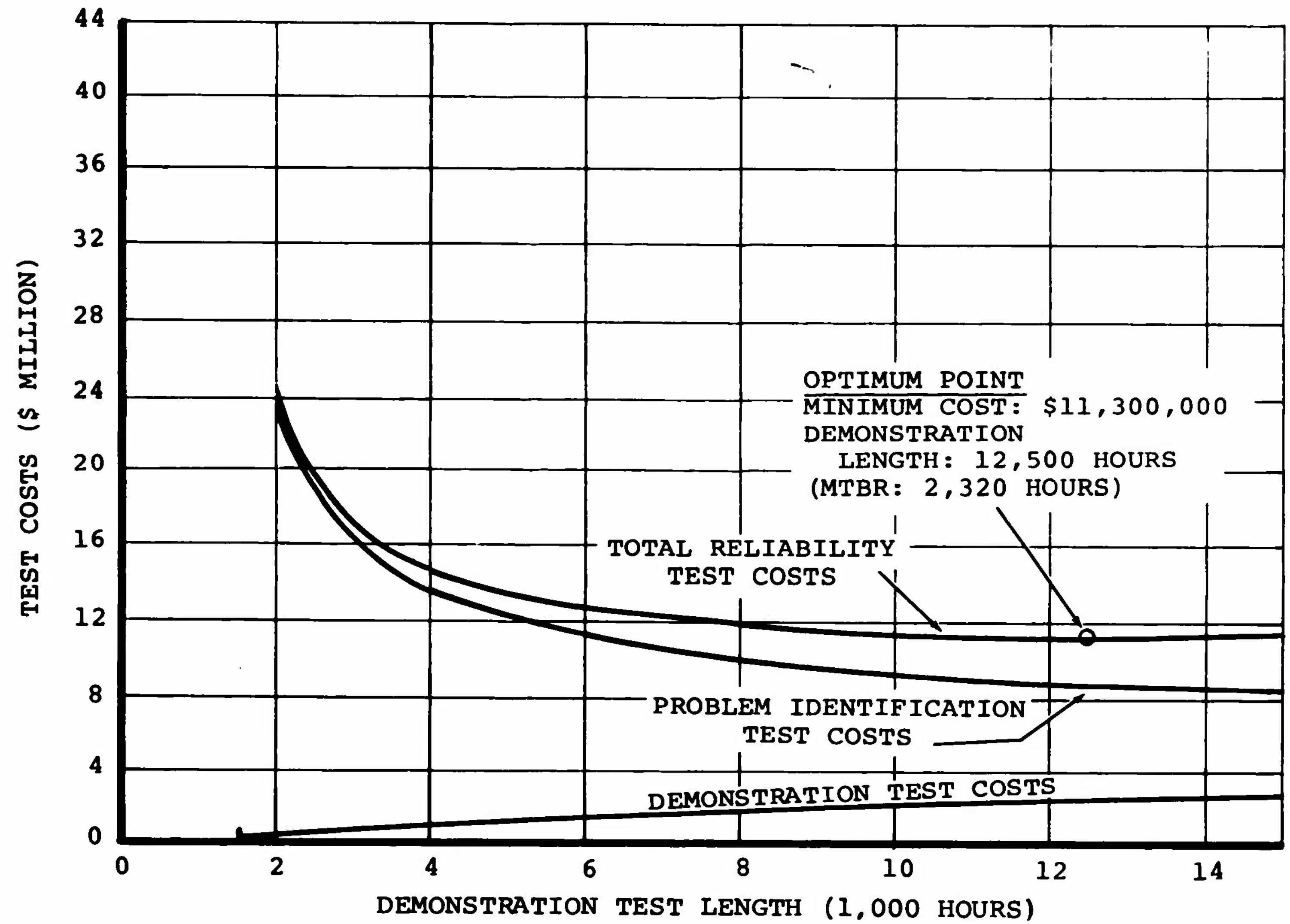


Figure 132. Total Reliability Test Costs Trade-Off Study for 1,500-Hour MTBR* at 60% Confidence, 80% Probability of Passing Demonstration, and 4-Year Demo-Out.

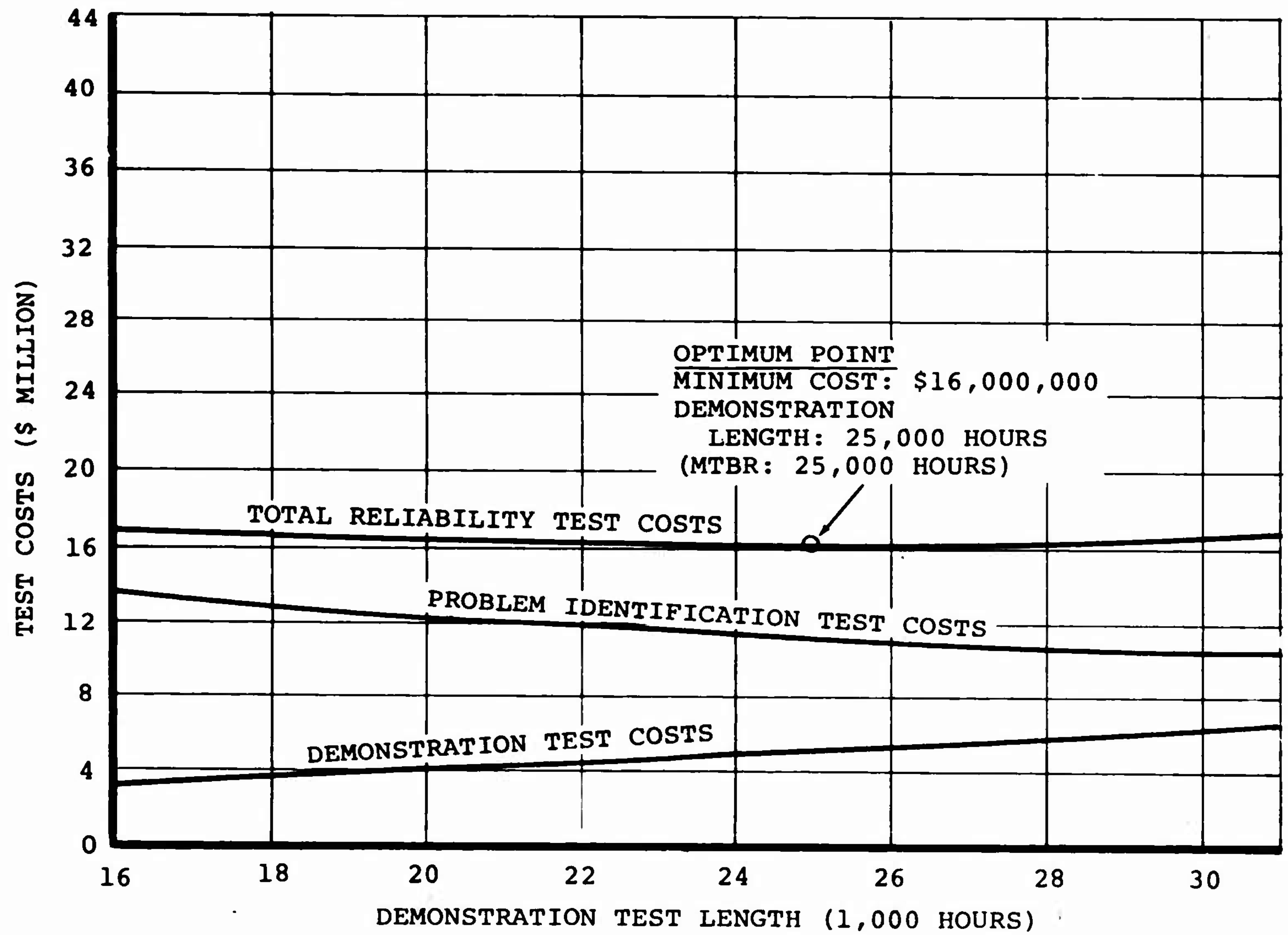


Figure 133. Total Reliability Test Costs Trade-Off Study for 1,500-Hour MTBR* at 90% Confidence, 80% Probability of Passing Demonstration, and 4-Year Demo-Out.

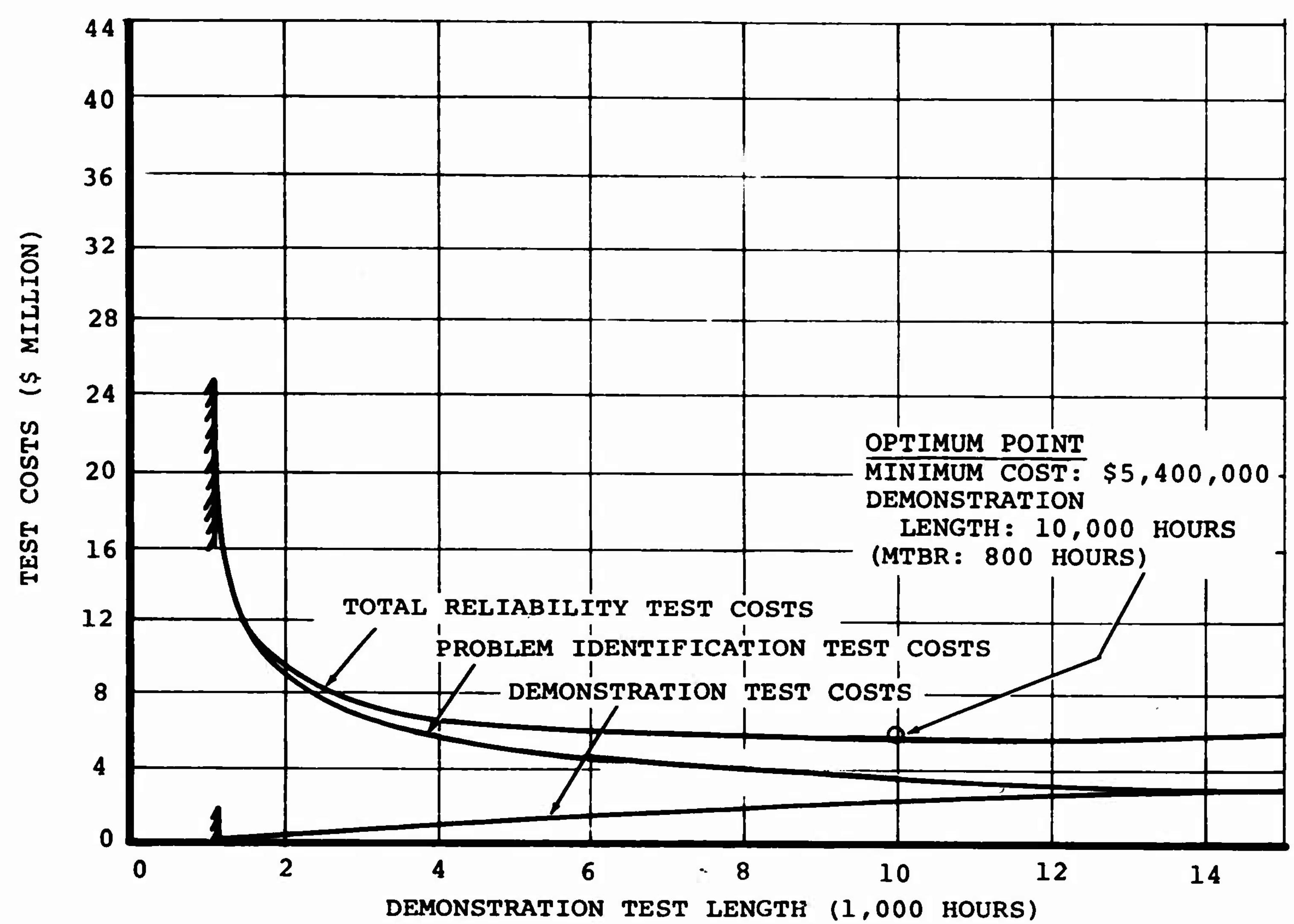


Figure 134. Total Reliability Test Costs Trade-Off Study for 500-Hour MTBR* at 90% Confidence, 80% Probability of Passing Demonstration, and 6-Year Demo-Out.

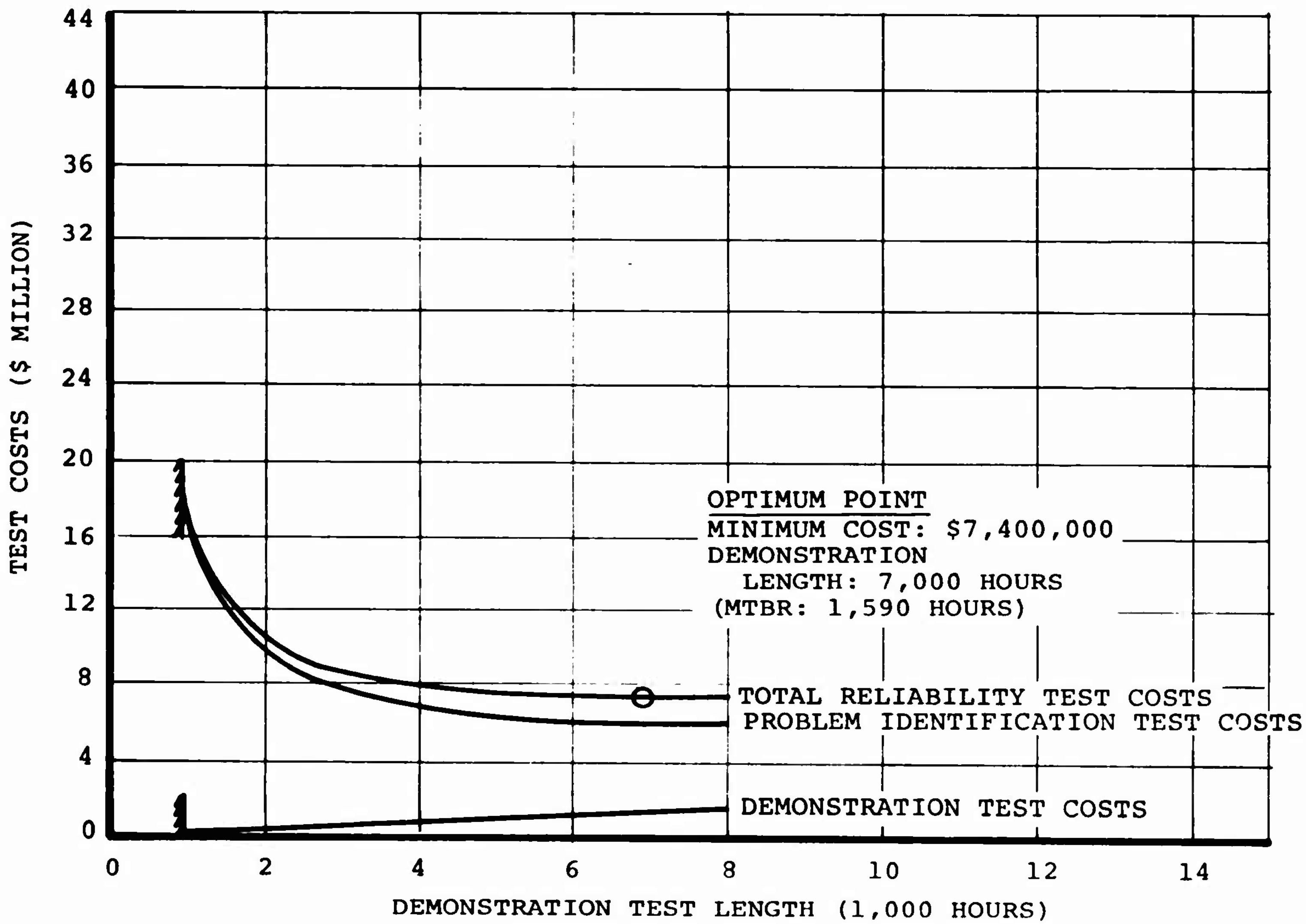


Figure 135. Total Reliability Test Costs Trade-Off Study for 1,000-Hour MTBR* at 60% Confidence, 80% Probability of Passing Demonstration, and 6-Year Demo-Out.

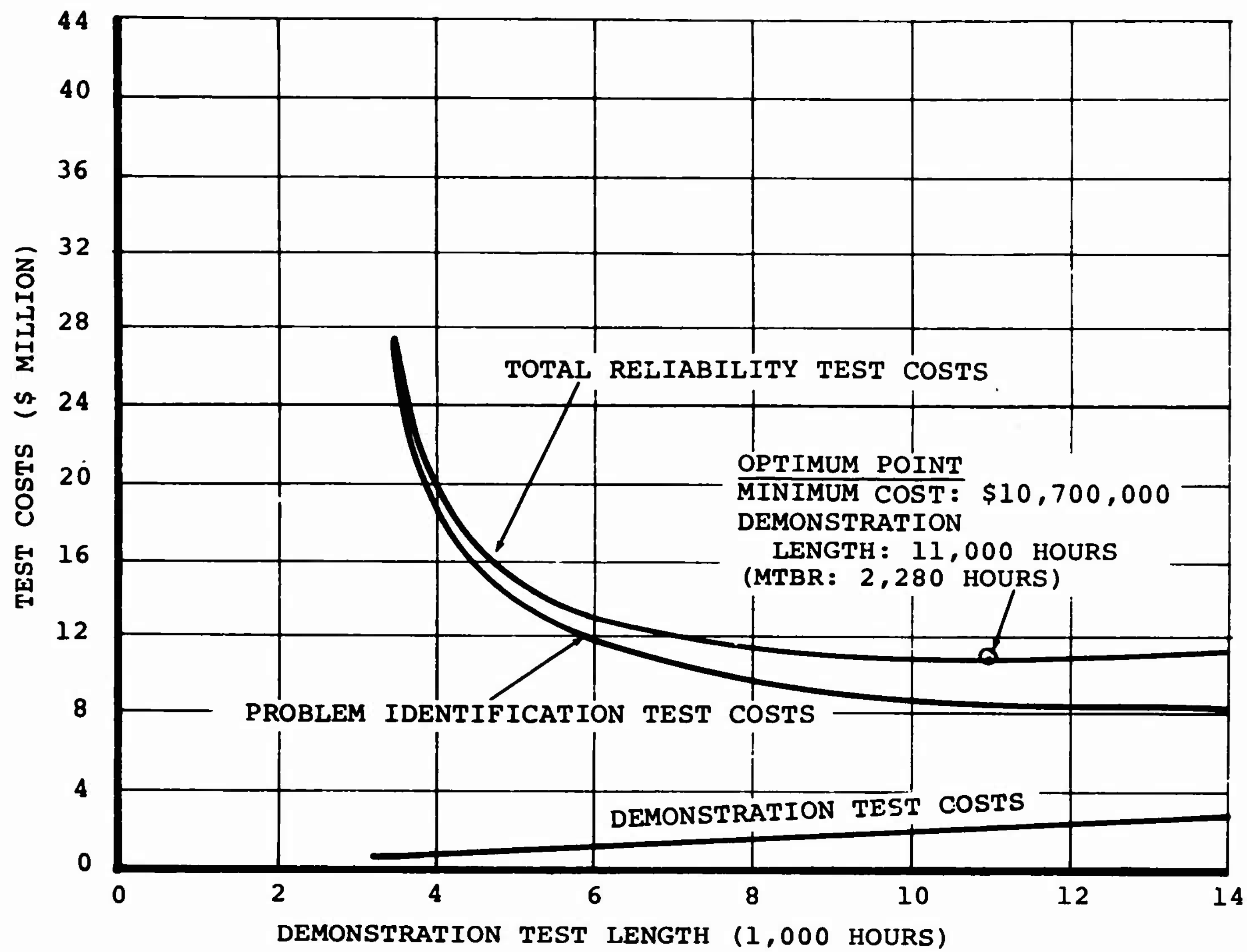


Figure 136. Total Reliability Test Costs Trade-Off Study for 1,000-Hour MTBR* at 90% Confidence, 80% Probability of Passing Demonstration, and 6-Year Demo-Out.

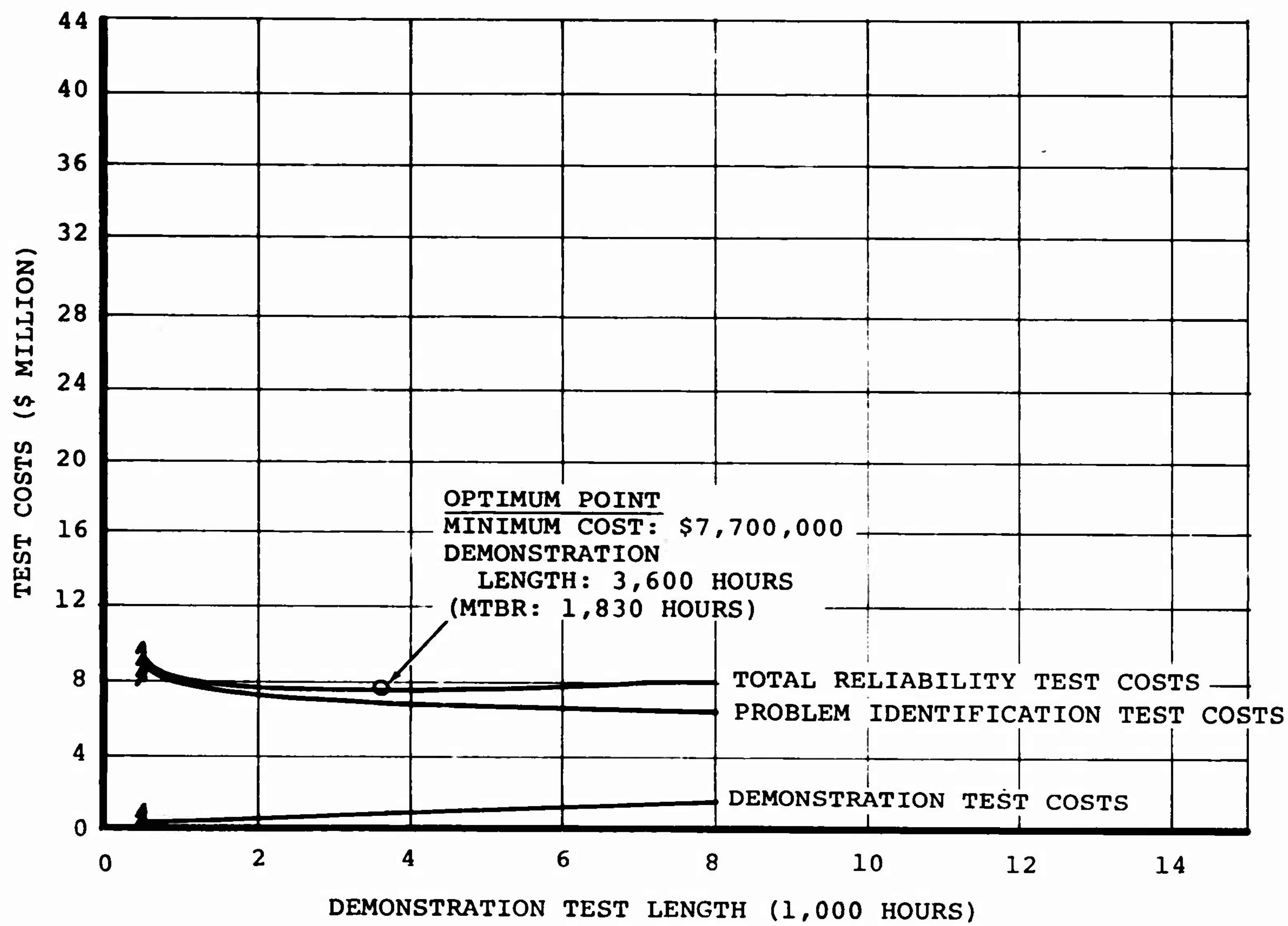


Figure 137. Total Reliability Test Costs Trade-Off Study for 1,500-Hour MTBR* at 30% Confidence, 80% Probability of Passing Demonstration, and 6-Year Demo-Out.

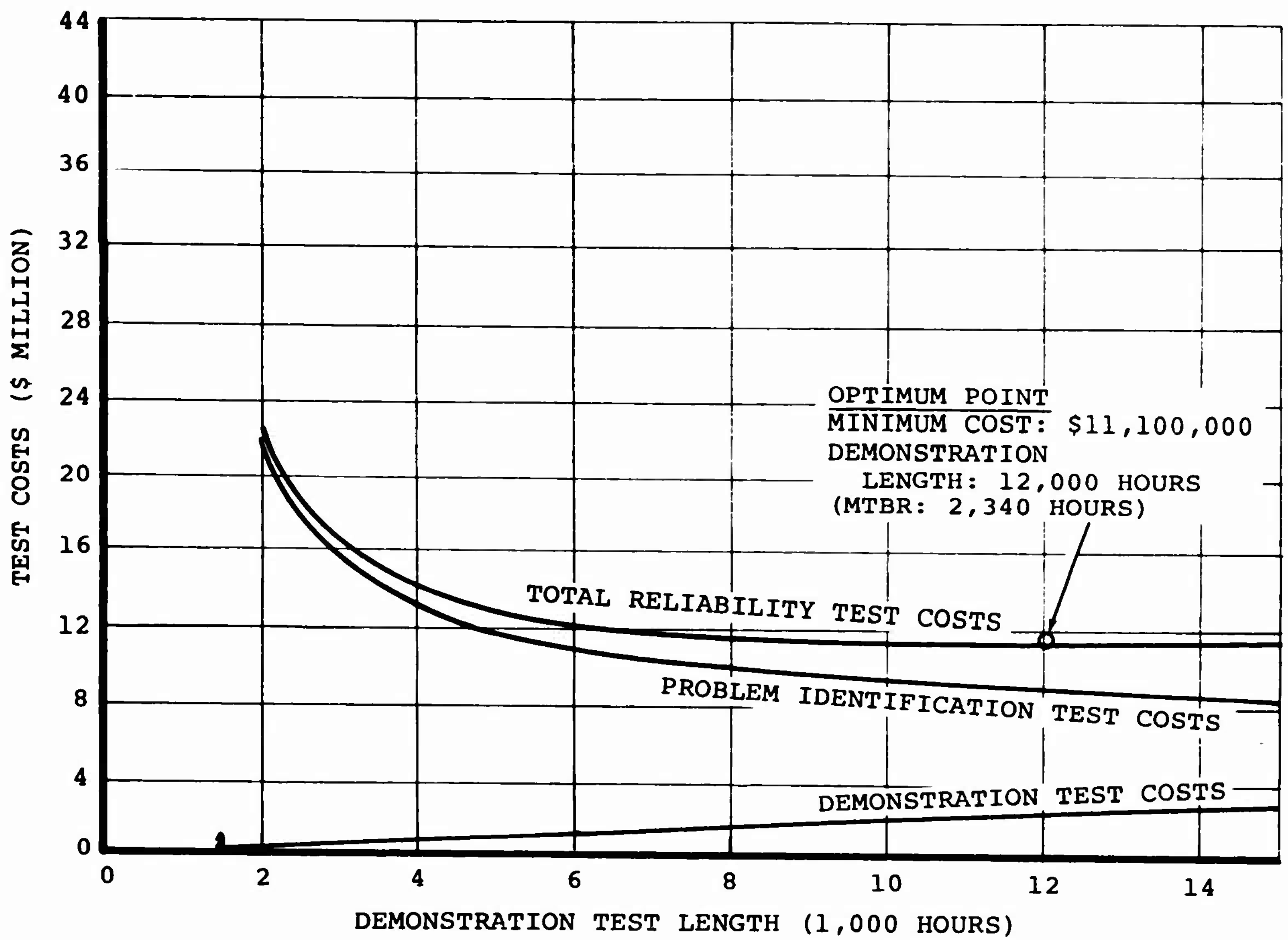


Figure 138. Total Reliability Test Costs Trade-Off Study for 1,500-Hour MTBR* at 60% Confidence, 80% Probability of Passing Demonstration, and 6-Year Demo-Out.

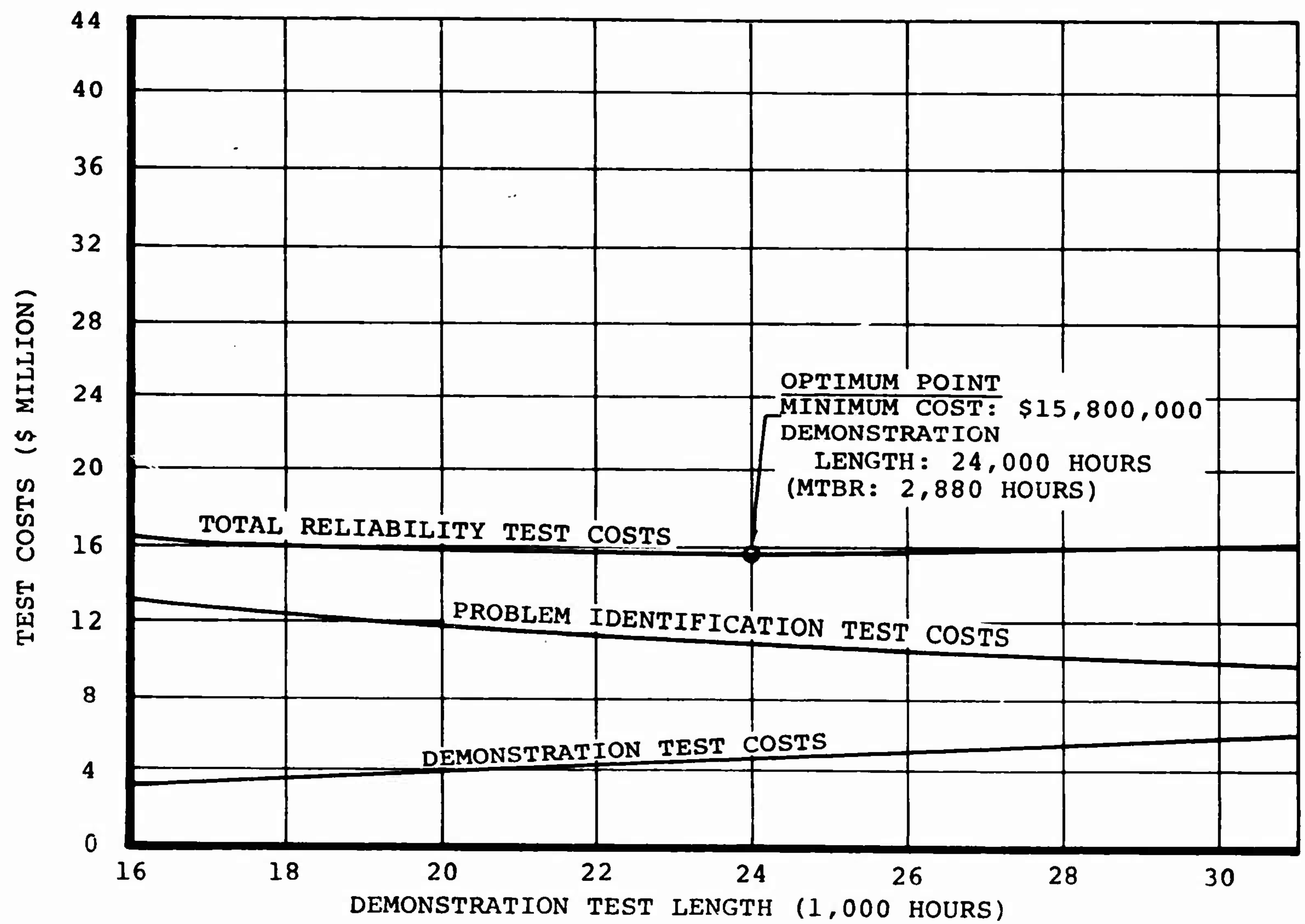


Figure 139. Total Reliability Test Costs Trade-Off Study for 1,500-Hour MTBR* at 90% Confidence, 80% Probability of Passing Demonstration, and 6-Year Demo-Out.

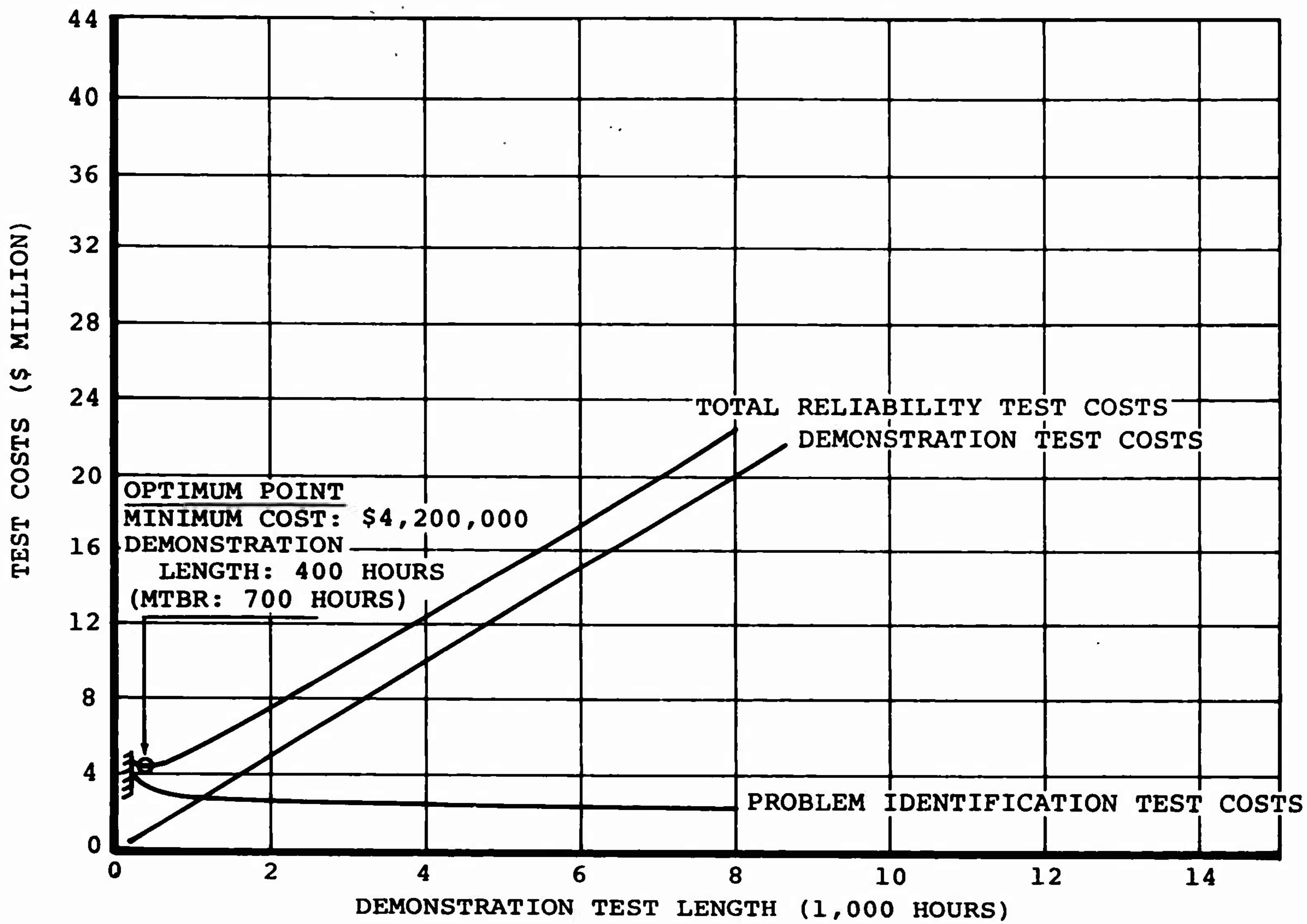


Figure 140. Total Reliability Test Costs Trade-Off Study for 500-Hour MTBR* at 30% Confidence, 80% Probability of Passing Demonstration, and 4-Year Demo-In.

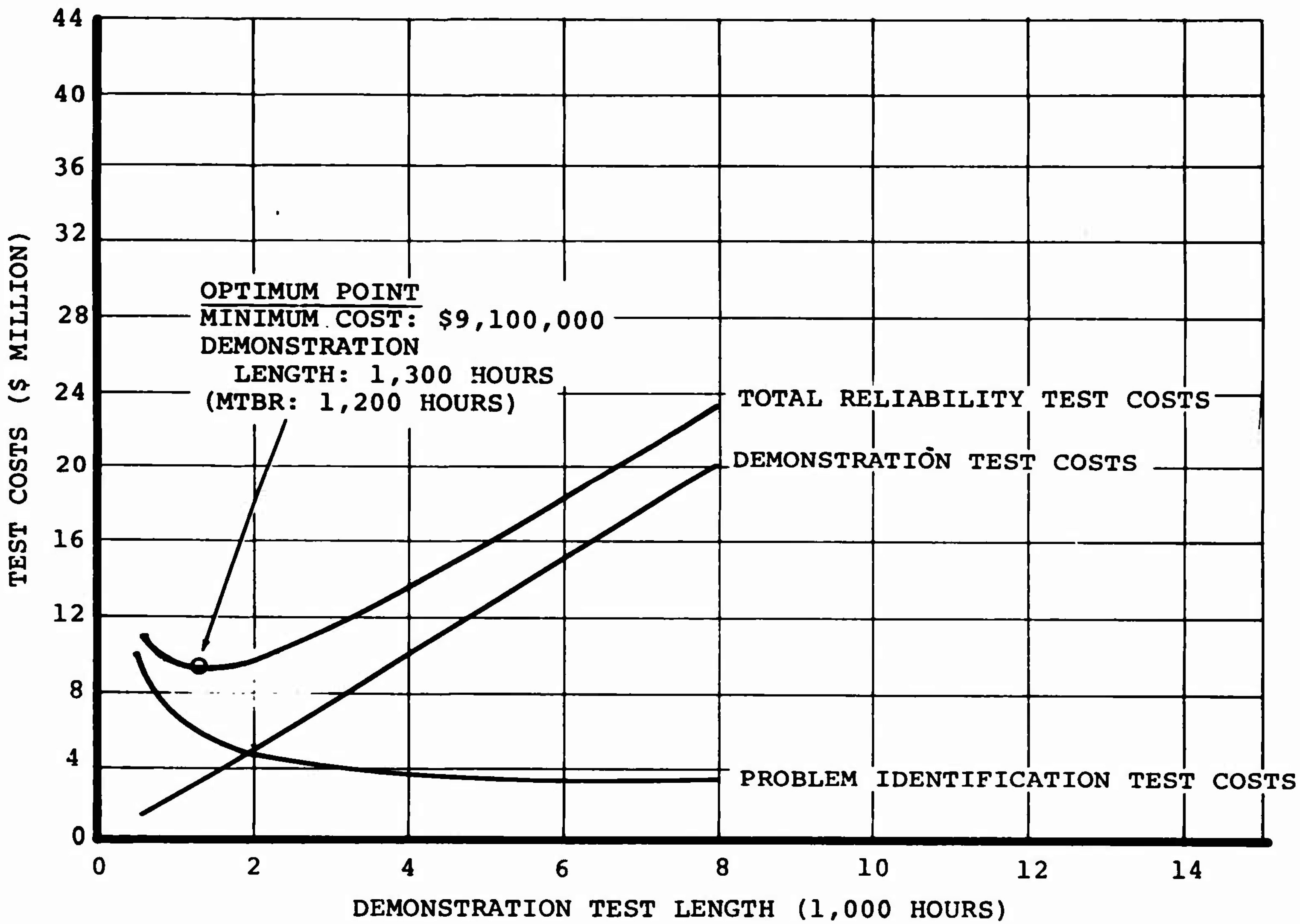


Figure 141. Total Reliability Test Costs Trade-Off Study for 500-Hour MTBR* at 60% Confidence, 80% Probability of Passing Demonstration, and 4-Year Demo-In.

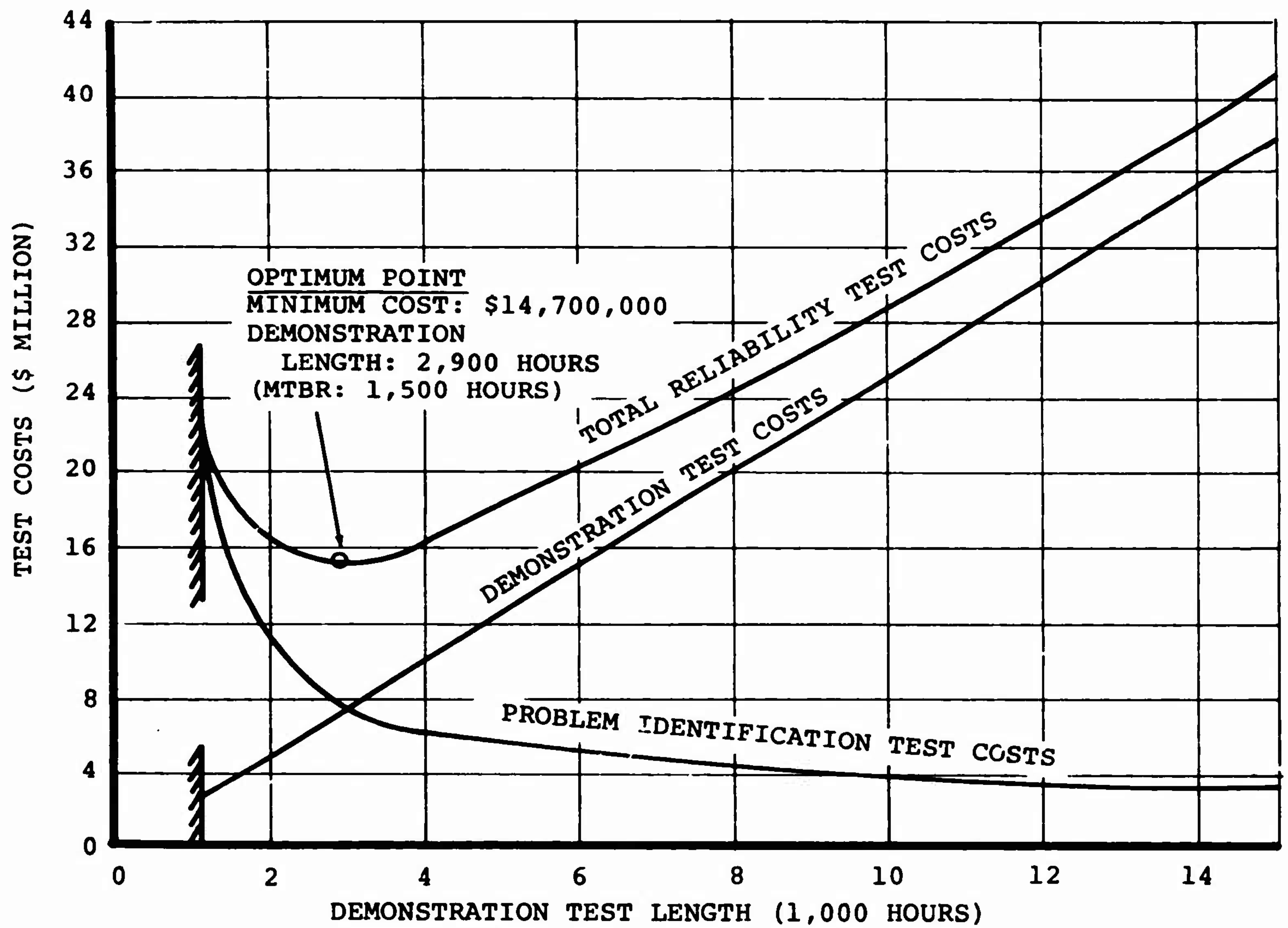


Figure 142. Total Reliability Test Costs Trade-Off Study for 500-Hour MTBR* at 90% Confidence, 80% Probability of Passing Demonstration, and 4-Year Demo-In.

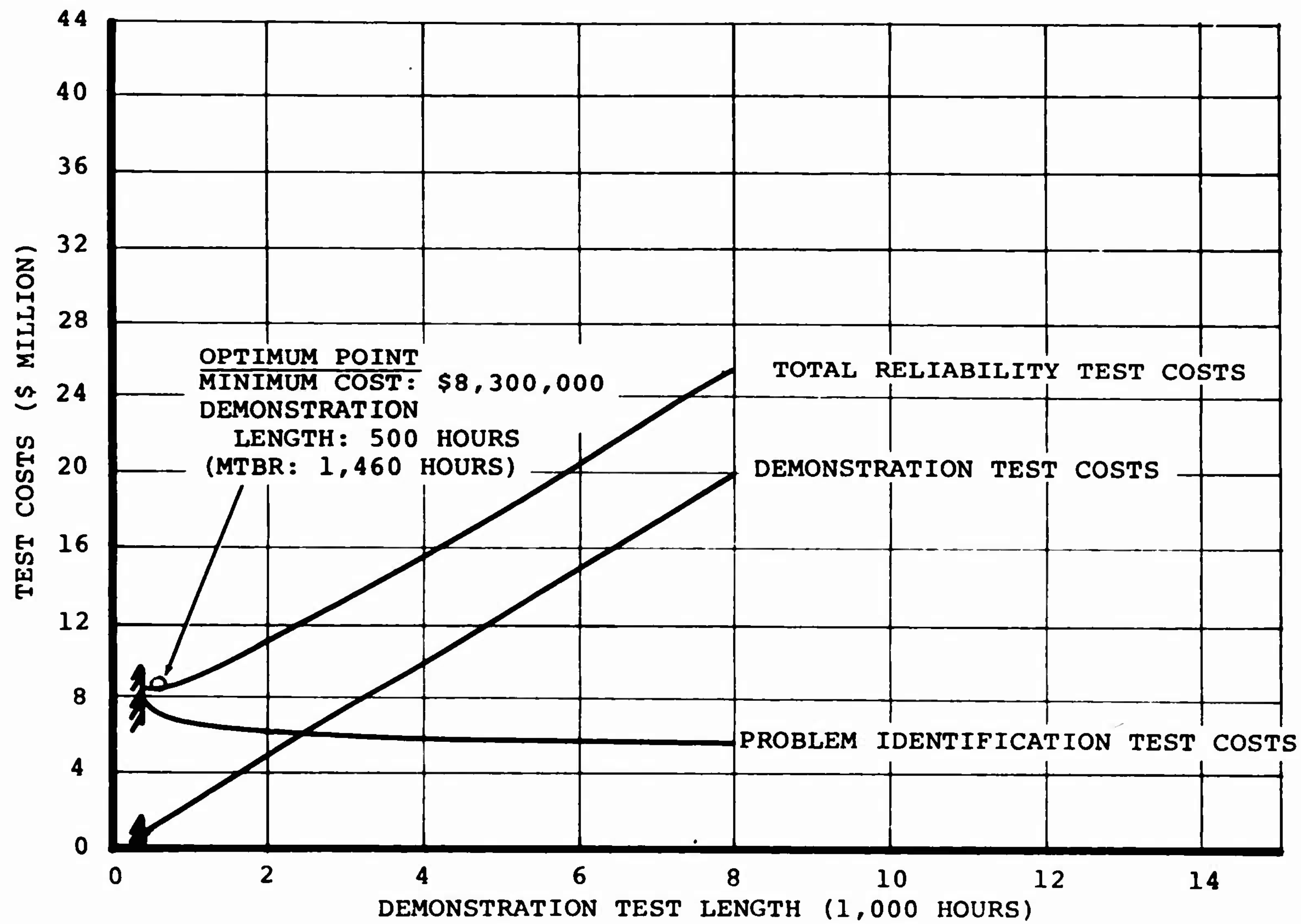
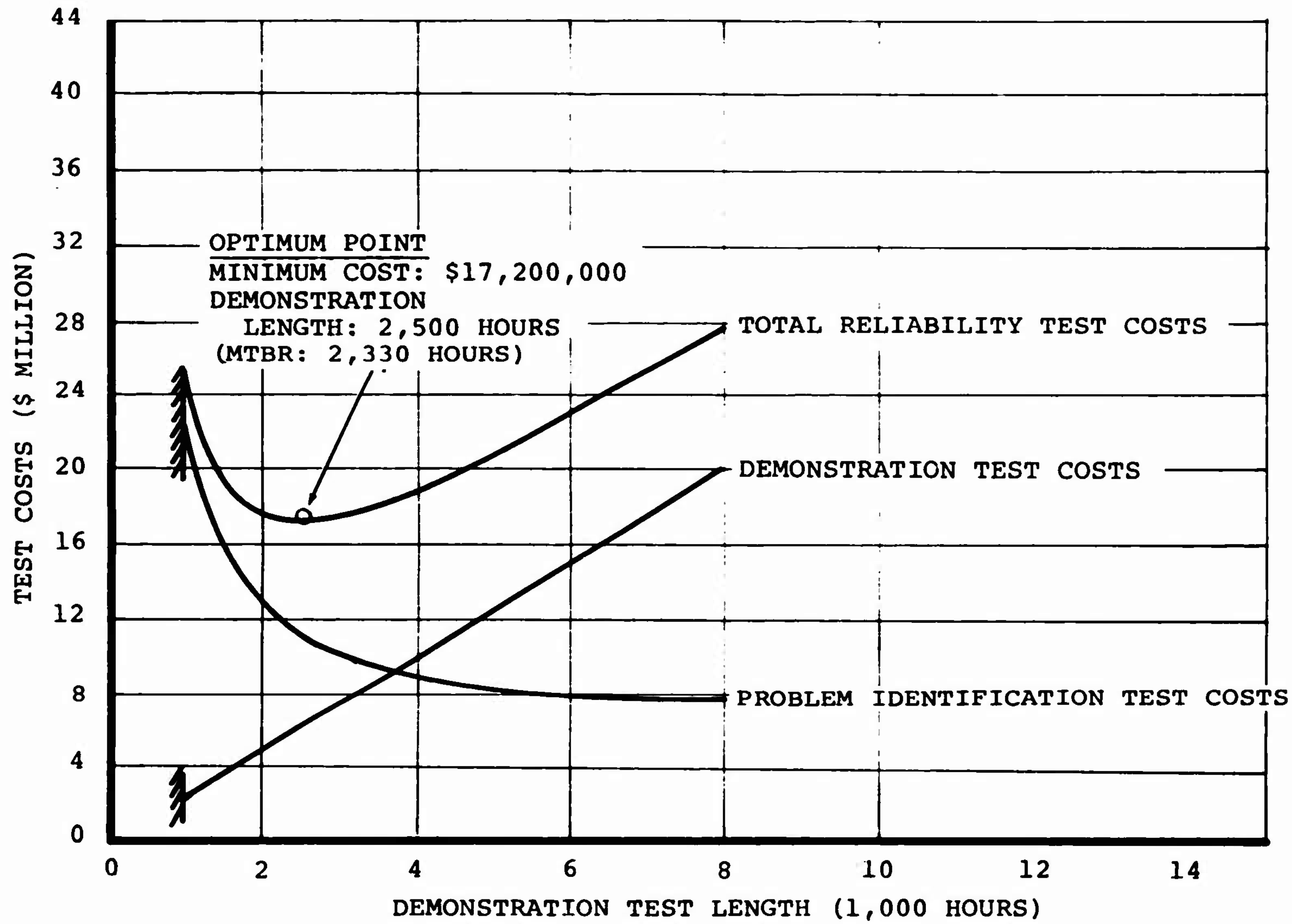


Figure 143. Total Reliability Test Costs Trade-Off Study for 1,000-Hour MTBR* at 30% Confidence, 80% Probability of Passing Demonstration, and 4-Year Demo-In.



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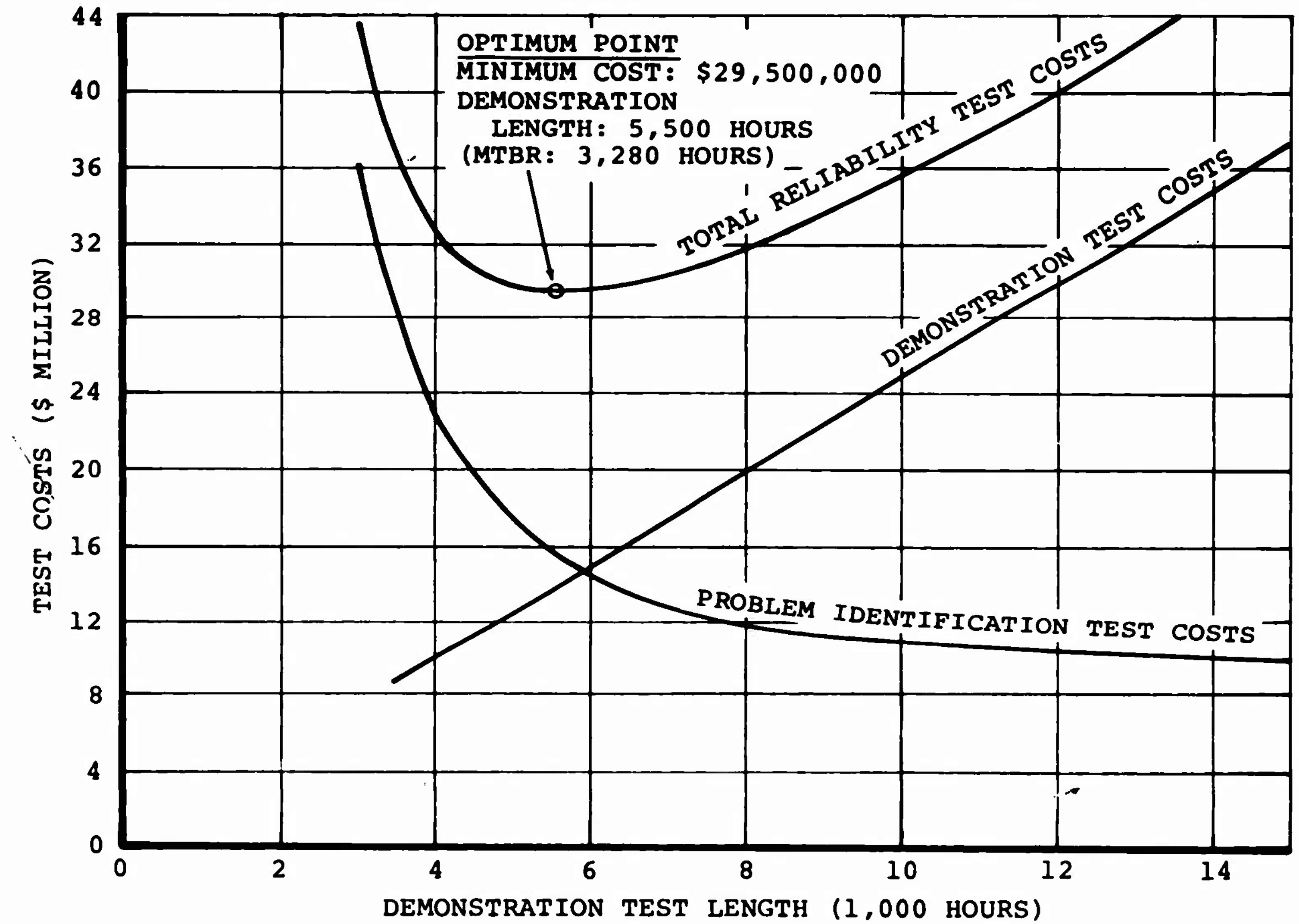

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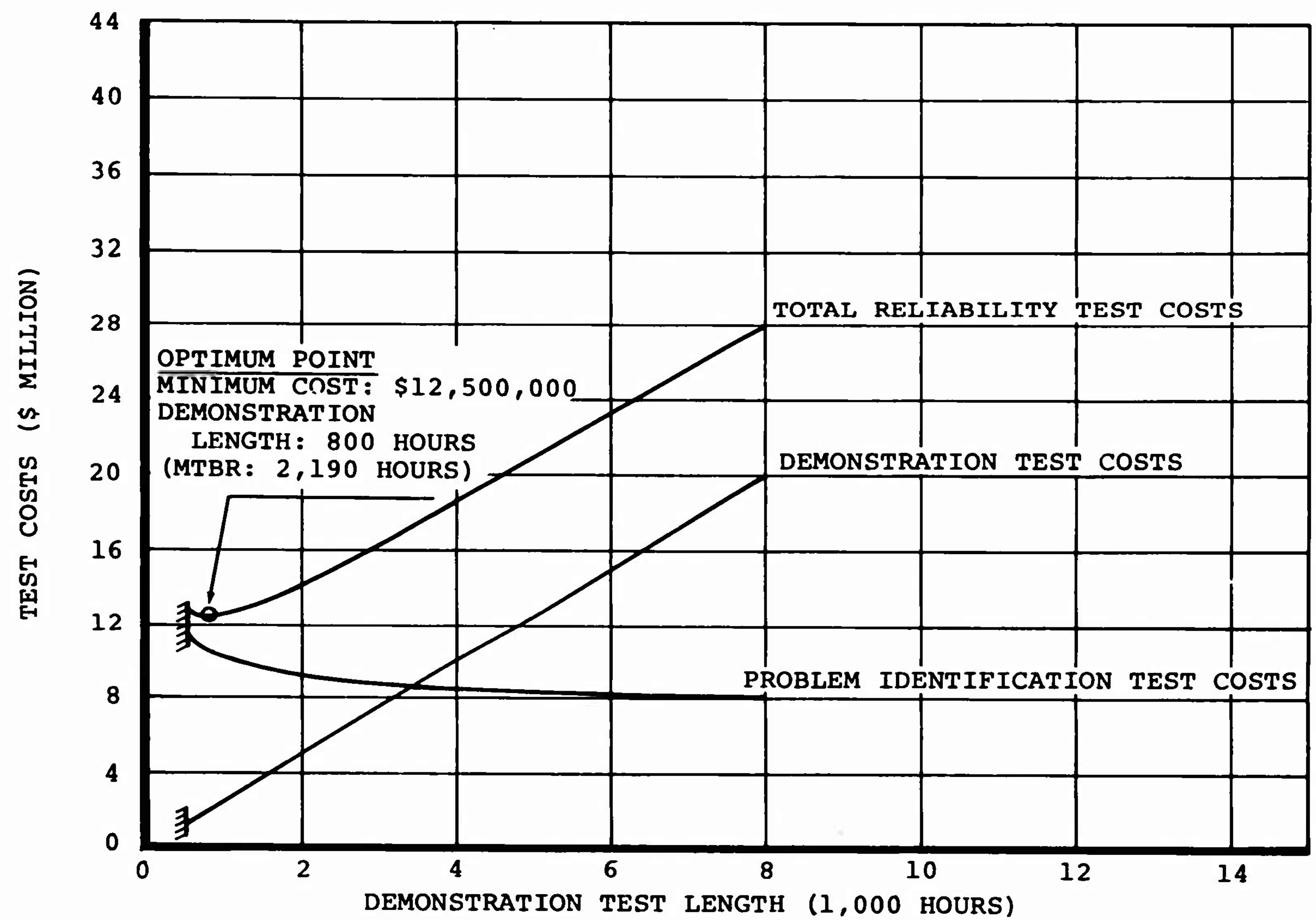

Figure 146. Total Reliability Test Costs Trade-Off Study for 1,500-Hour MTBR* at 30% Confidence, 80% Probability of Passing Demonstration, and 4-Year Demo-In.

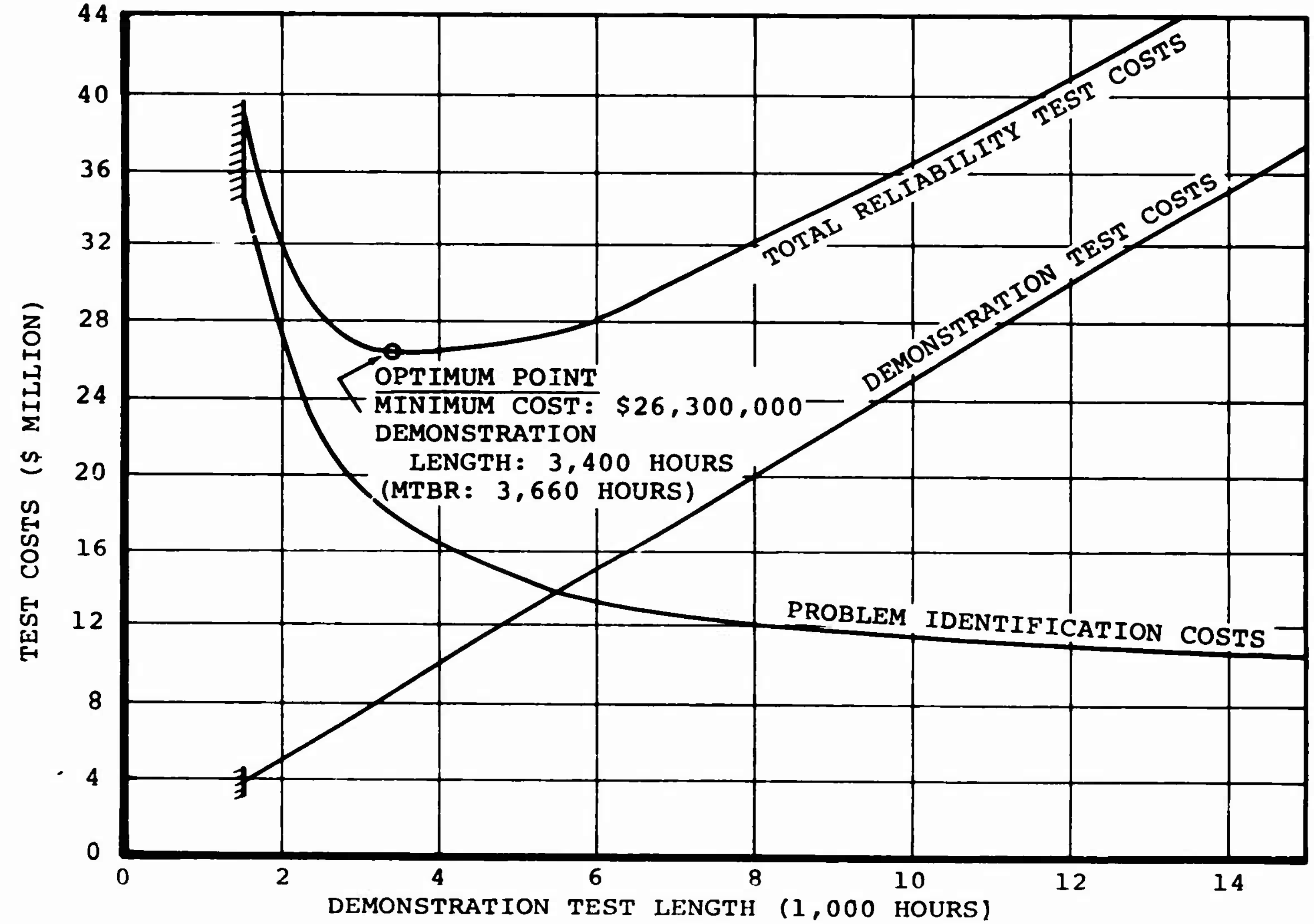

Figure 147. Total Reliability Test Costs Trade-Off Study for 1,500-Hour MTBR* at 60% Confidence, 80% Probability of Passing Demonstration, and 4-Year Demo-In.

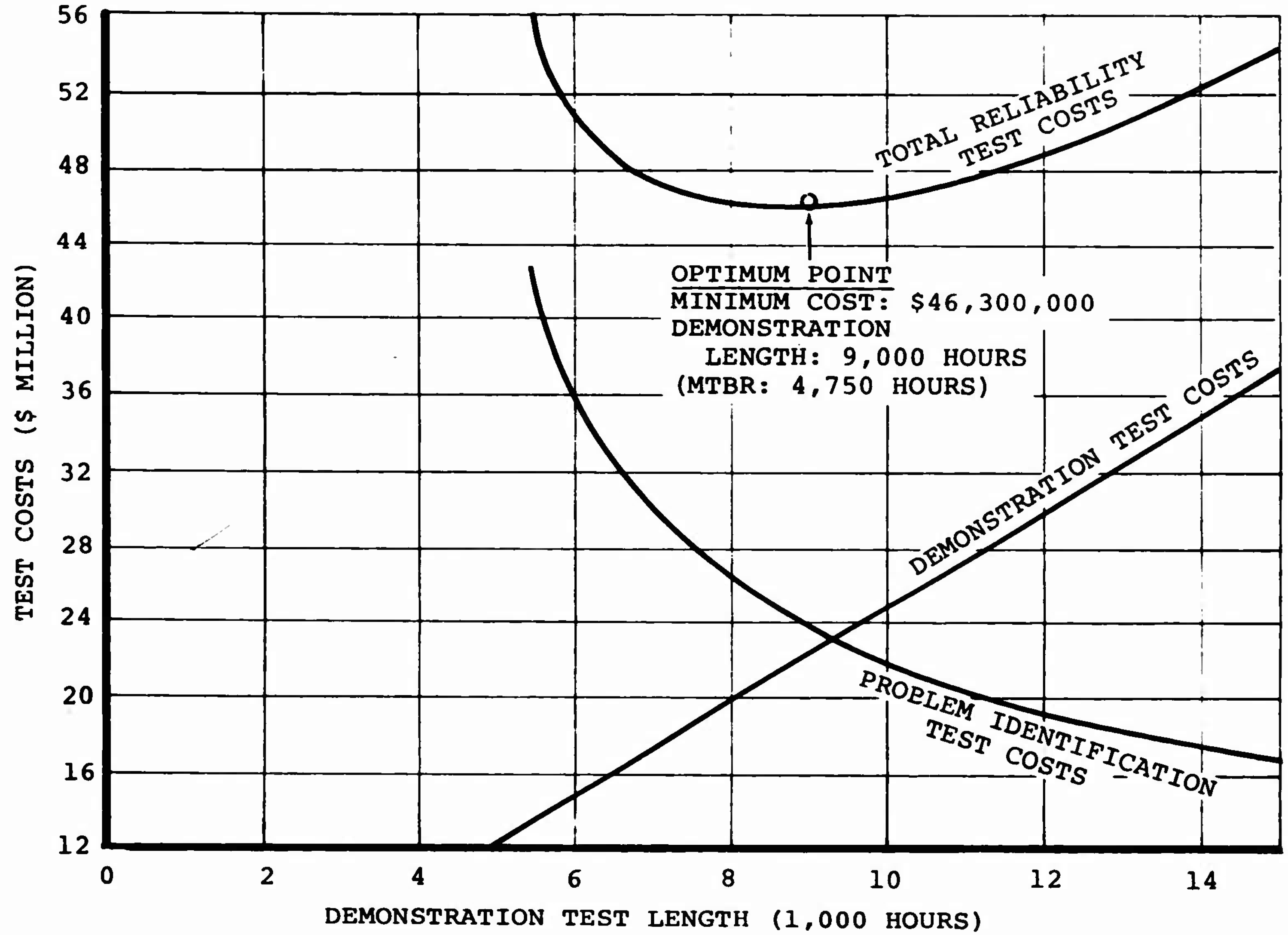

Figure 148. Total Reliability Test Costs Trade-Off Study for 1,500-Hour MTBR* at 90% Confidence, 80% Probability of Passing Demonstration, and 4-Year Demo-In.

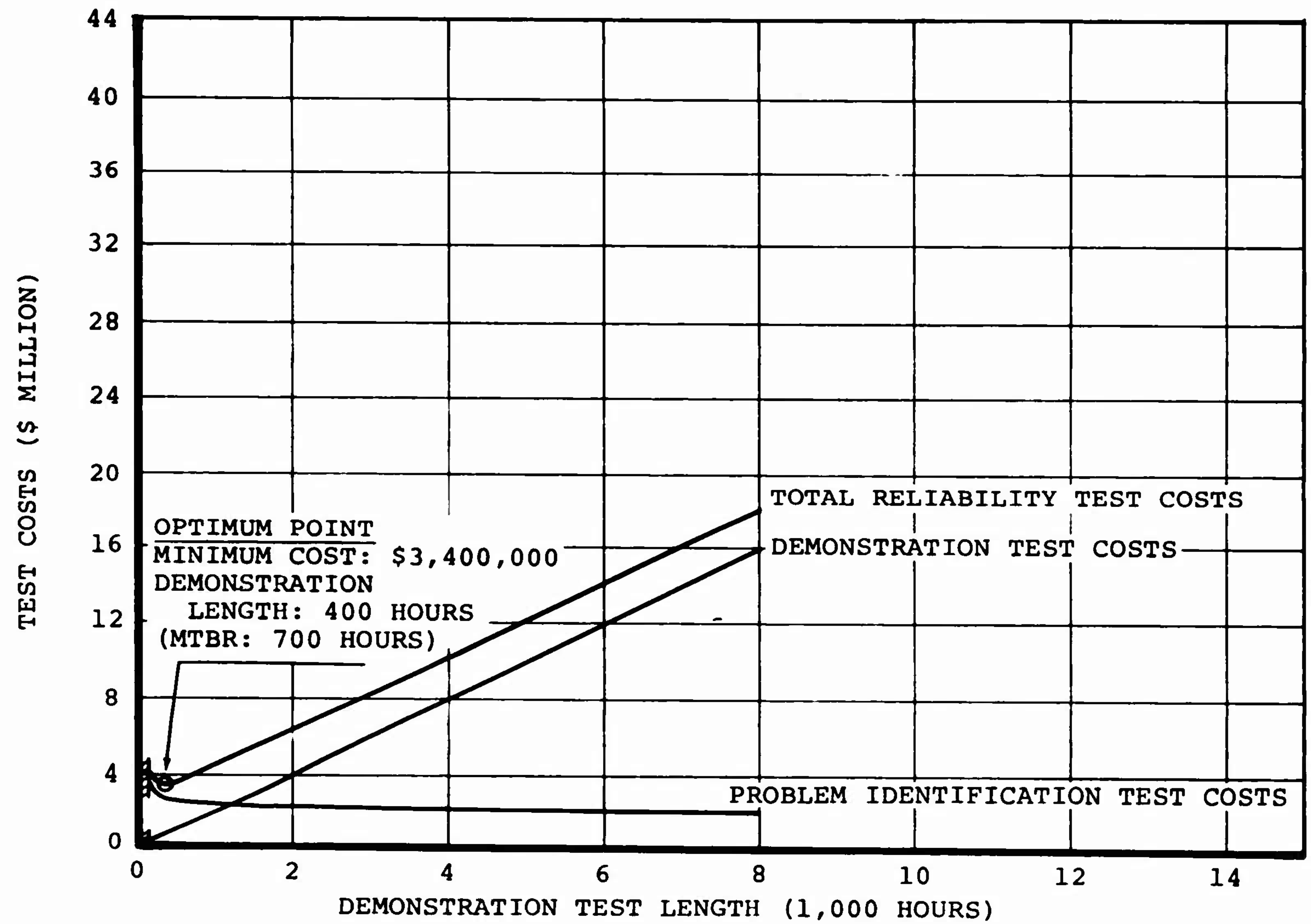

Figure 149. Total Reliability Test Costs Trade-Off Study for 500-Hour MTBR* at 30% Confidence, 80% Probability of Passing Demonstration, and 5- and 7-Year Demo-In.

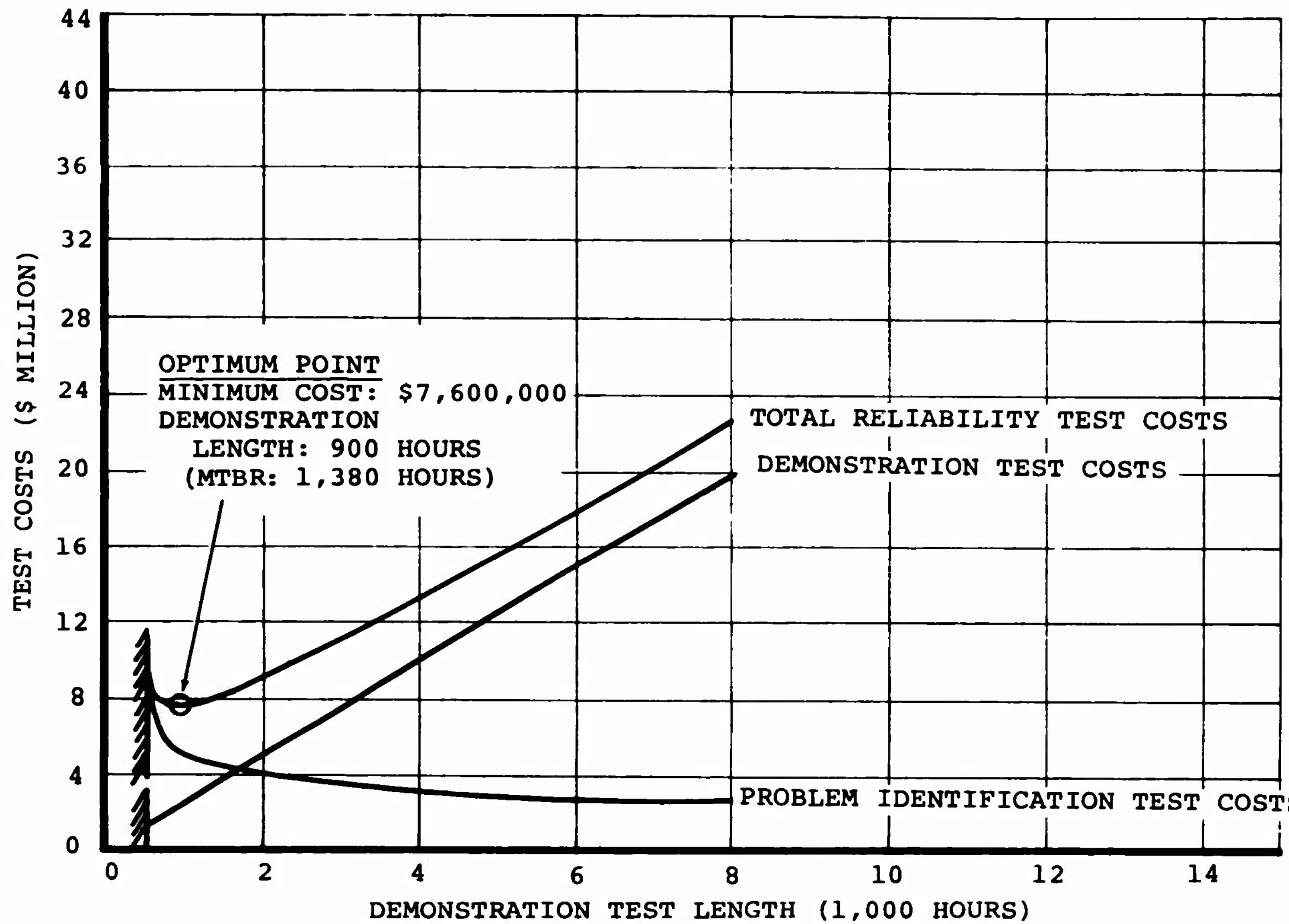

Figure 150. Total Reliability Test Costs Trade-Off Study for 500-Hour MTBR* at 60% Confidence, 80% Probability of Passing Demonstration, and 5- and 7-Year Demo-In.

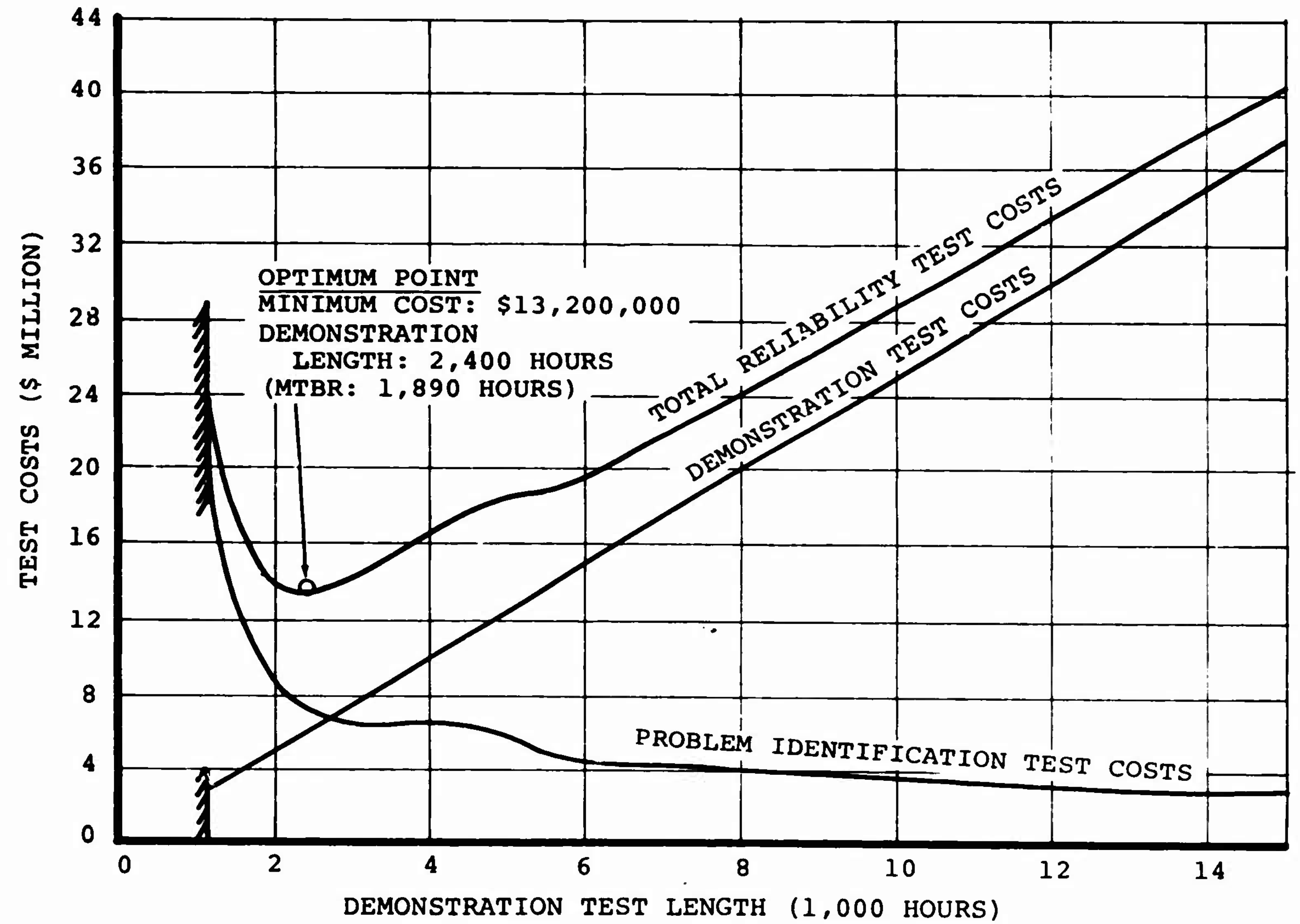

Figure 151. Total Reliability Test Costs Trade-Off Study for 500-Hour MTBR* at 90% Confidence, 80% Probability of Passing Demonstration, and 5-Year Demo-In.

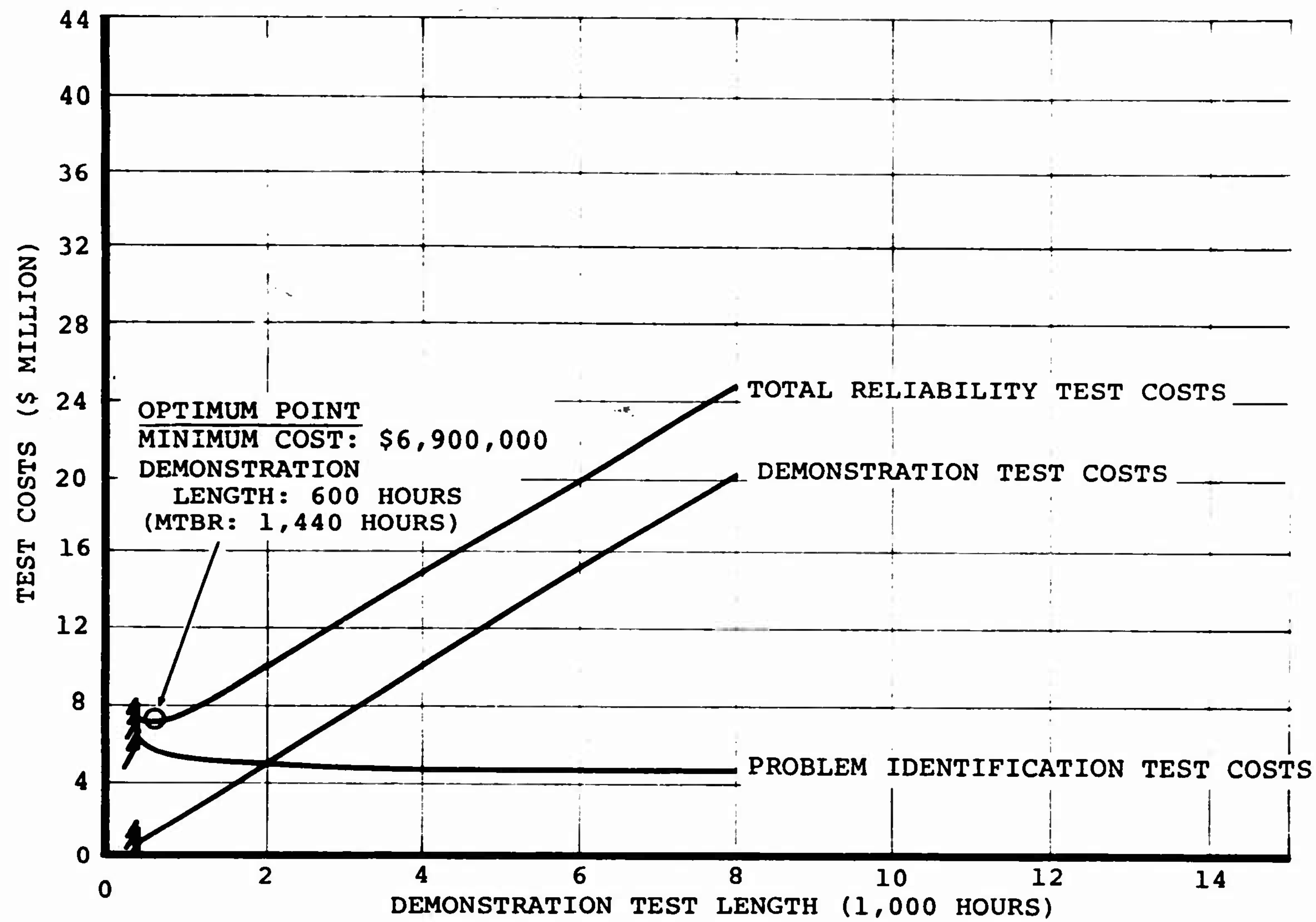

Figure 152. Total Reliability Test Costs Trade-Off Study for 1,000-Hour MTBR* at 30% Confidence, 80% Probability of Passing Demonstration, and 5- and 7-Year Demo-In.

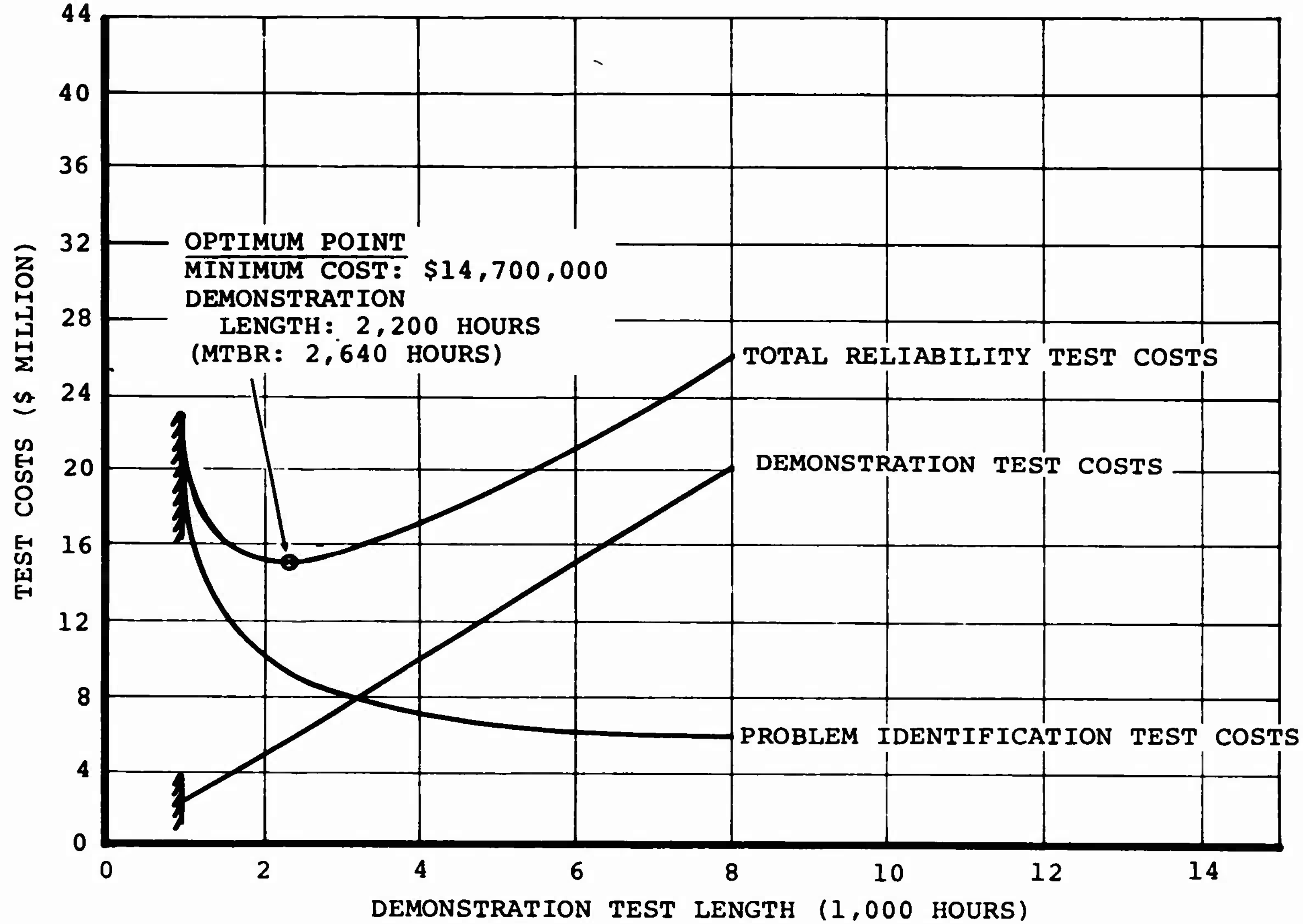

Figure 153. Total Reliability Test Costs Trade-Off Study for 1,000-Hour MTBR* at 60% Confidence, 80% Probability of Passing Demonstration, and 5-Year Demo-In.

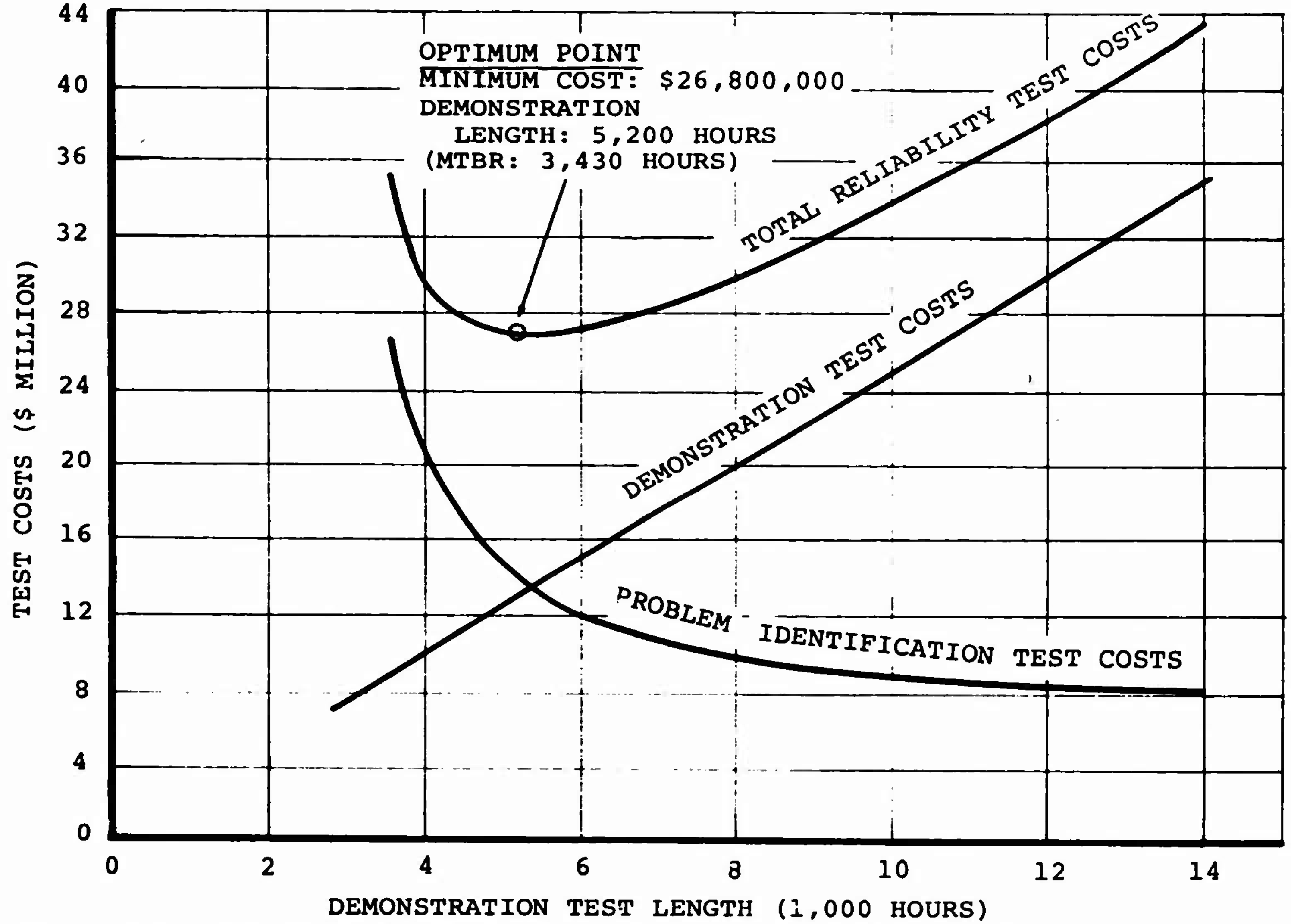

Figure 154. Total Reliability Test Costs Trade-Off Study for 1,000-Hour MTBR* at 90% Confidence, 80% Probability of Passing Demonstration, and 5-Year Demo-In.

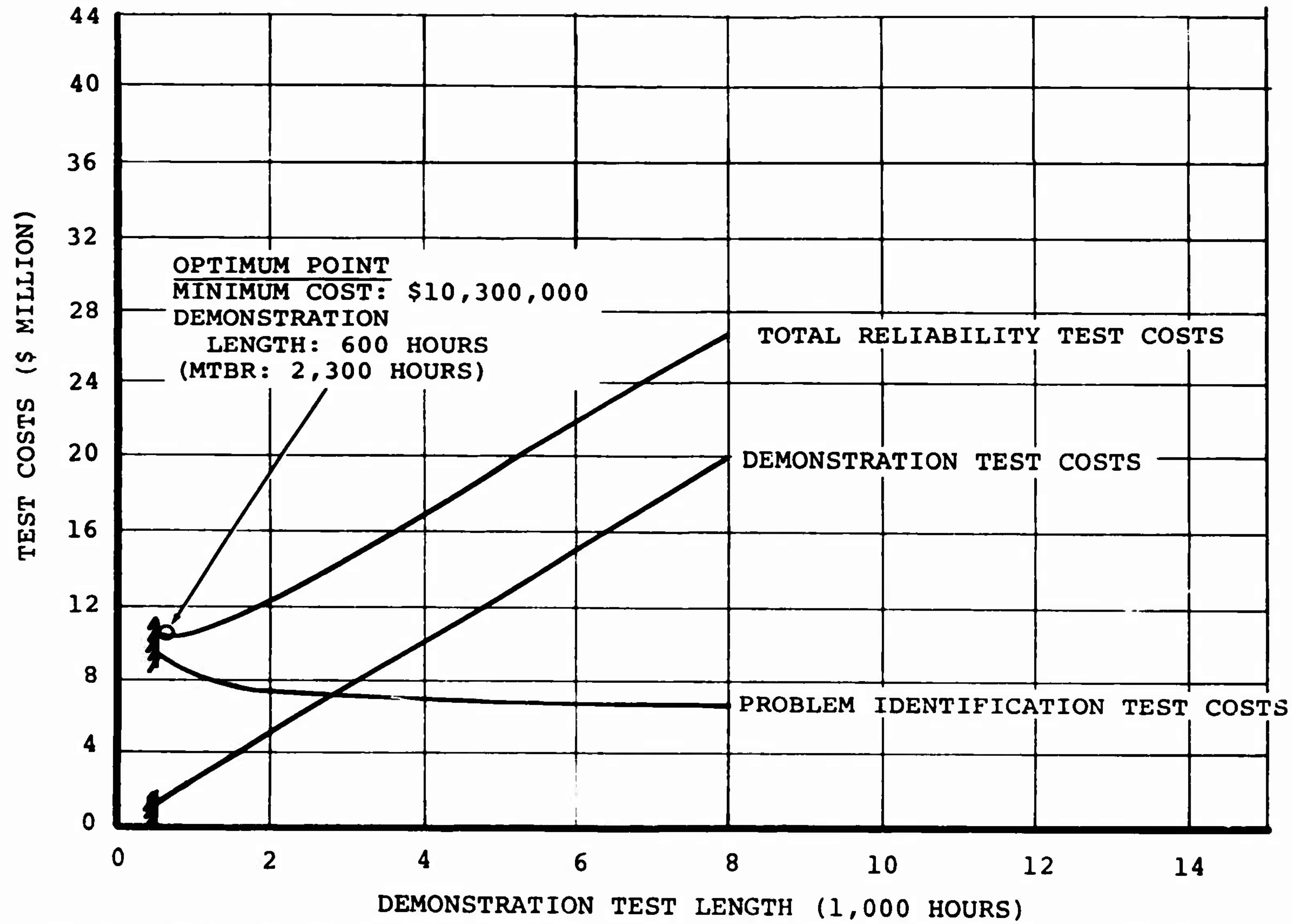

Figure 155. Total Reliability Test Costs Trade-Off Study for 1,500-Hour MTBR* at 30% Confidence, 80% Probability of Passing Demonstration, and 5-Year Demo-In.

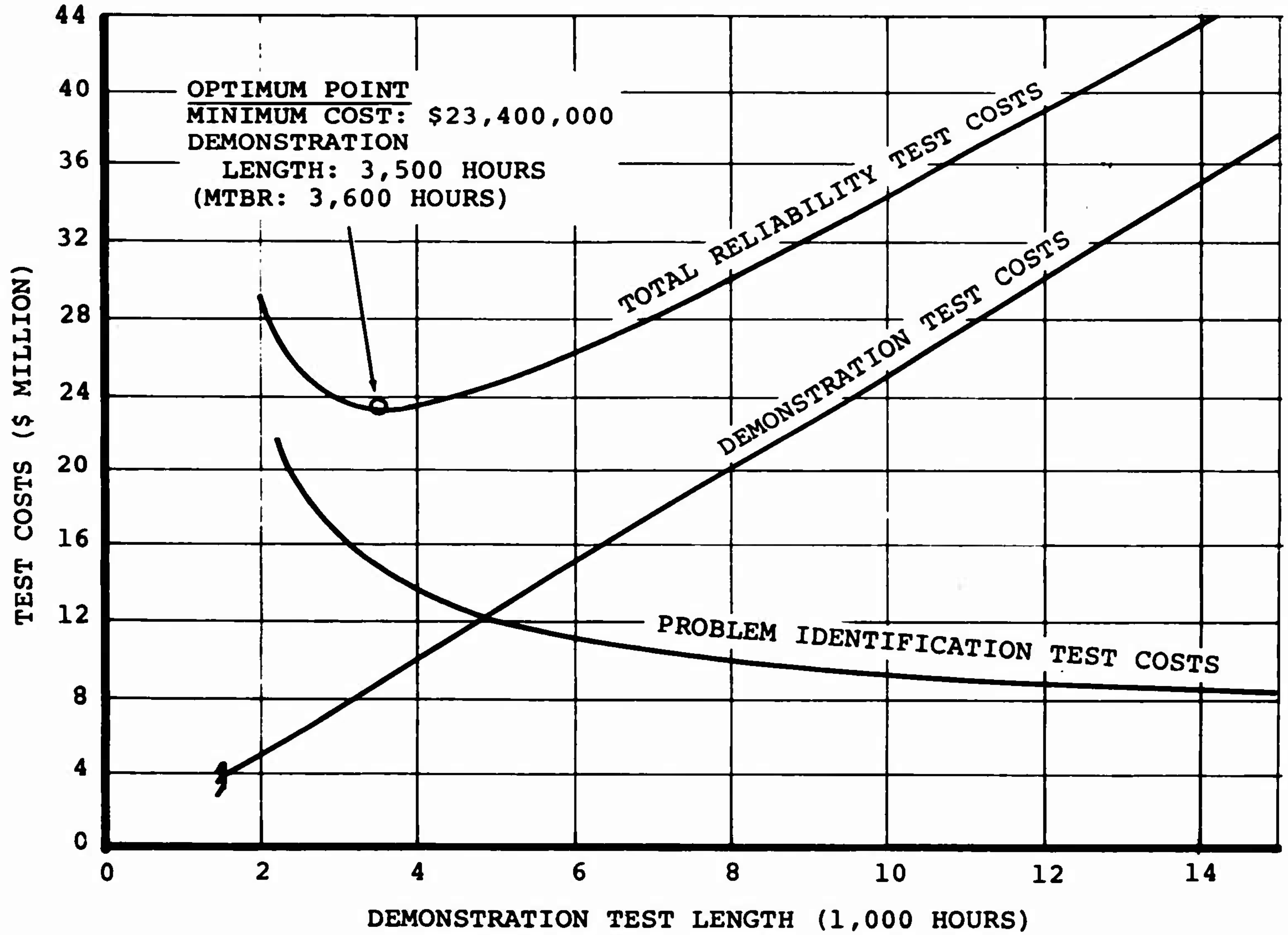

Figure 156. Total Reliability Test Costs Trade-Off Study for 1,500-Hour MTBR* at 60% Confidence, 80% Probability of Passing Demonstration, and 5-Year Demo-In.

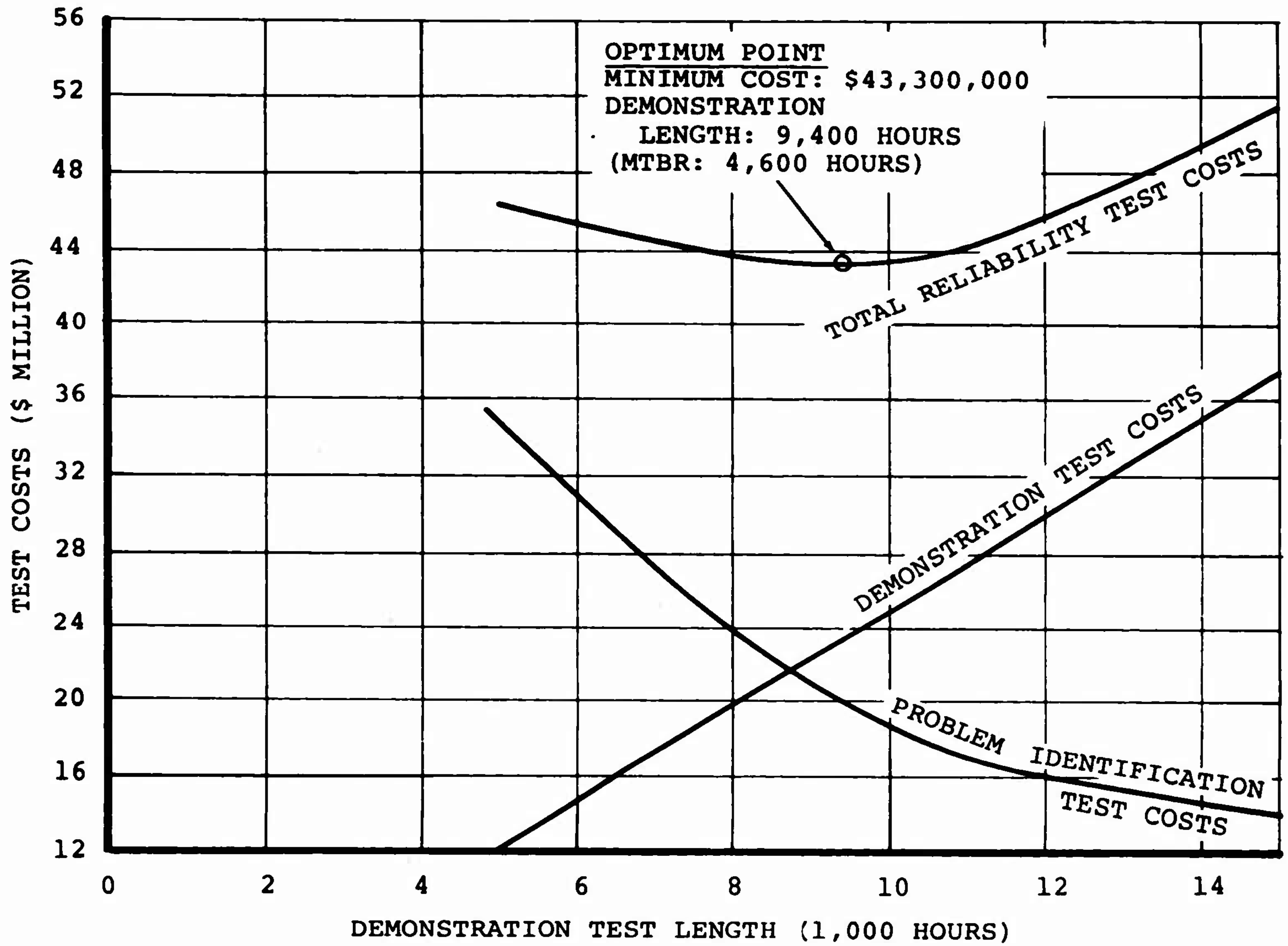

Figure 157. Total Reliability Test Costs Trade-Off Study for 1,500-Hour MTBR* at 90% Confidence, 80% Probability of Passing Demonstration, and 5-Year Demo-In.

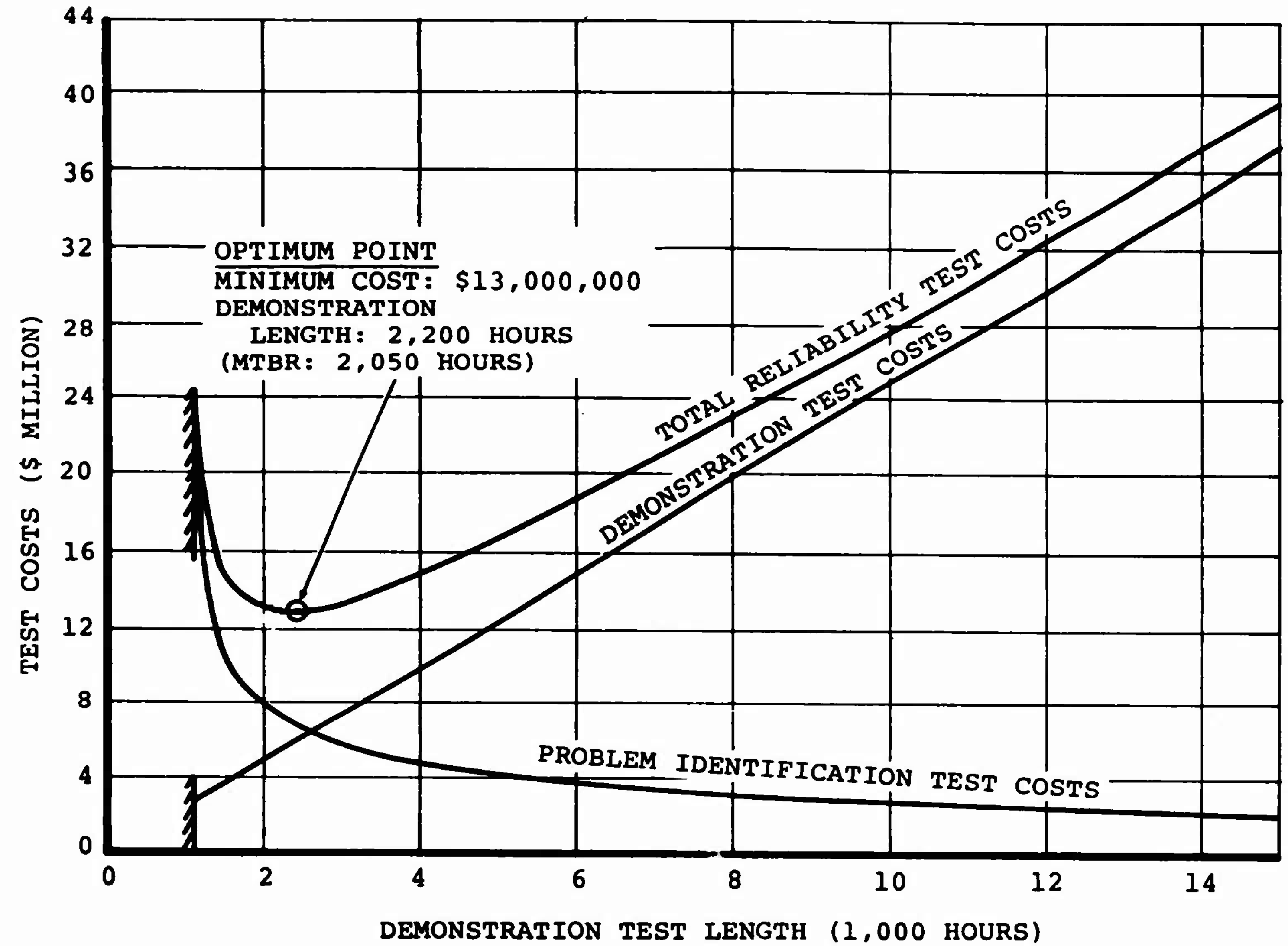

Figure 158. Total Reliability Test Costs Trade-Off Study for 500-Hour MTBR* at 90% Confidence, 80% Probability of Passing Demonstration, and 7-Year Demo-In.

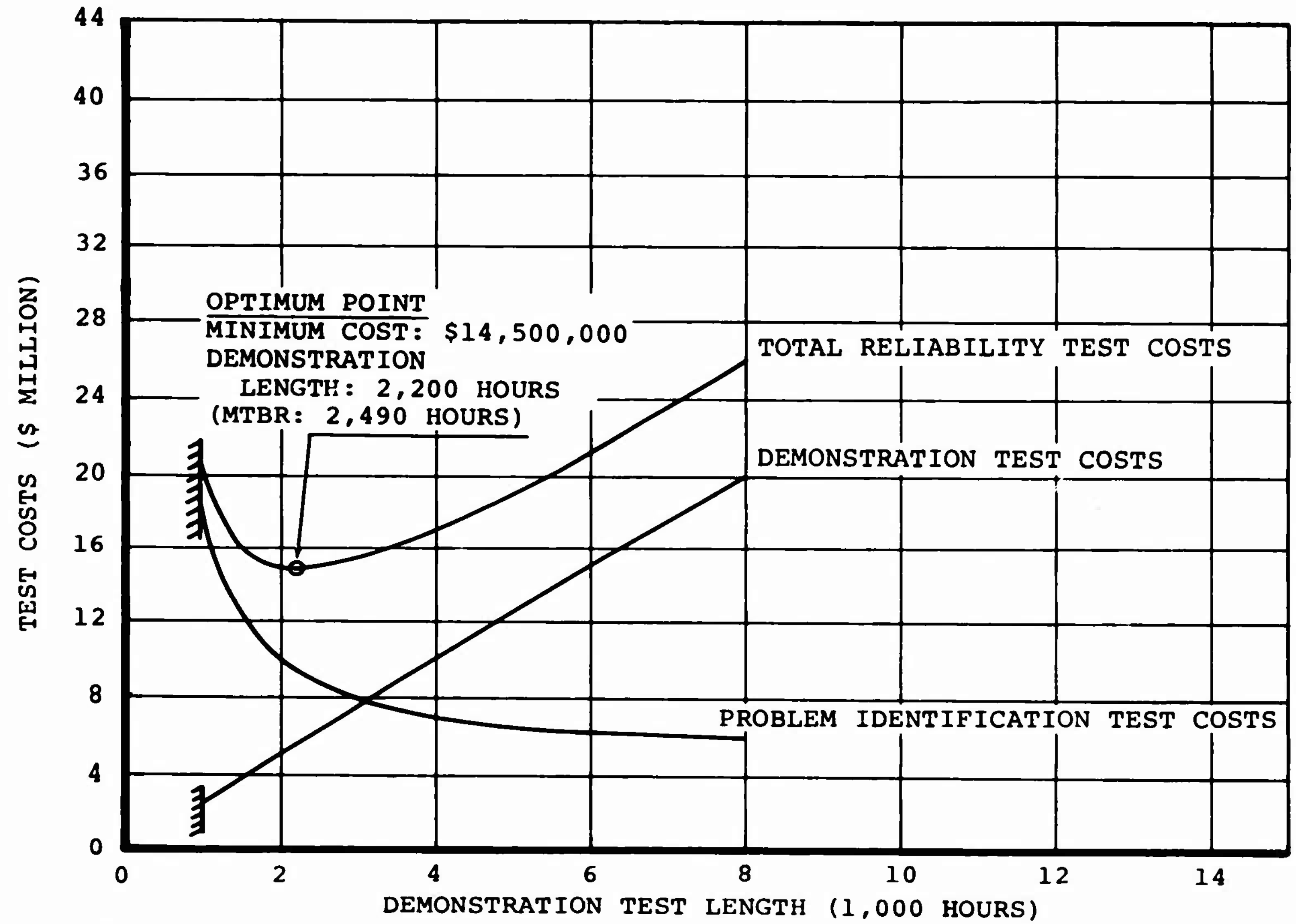

Figure 159. Total Reliability Test Costs Trade-Off Study for 1,000-Hour MTBR* at 60% Confidence, 80% Probability of Passing Demonstration, and 7-Year Demo-In.

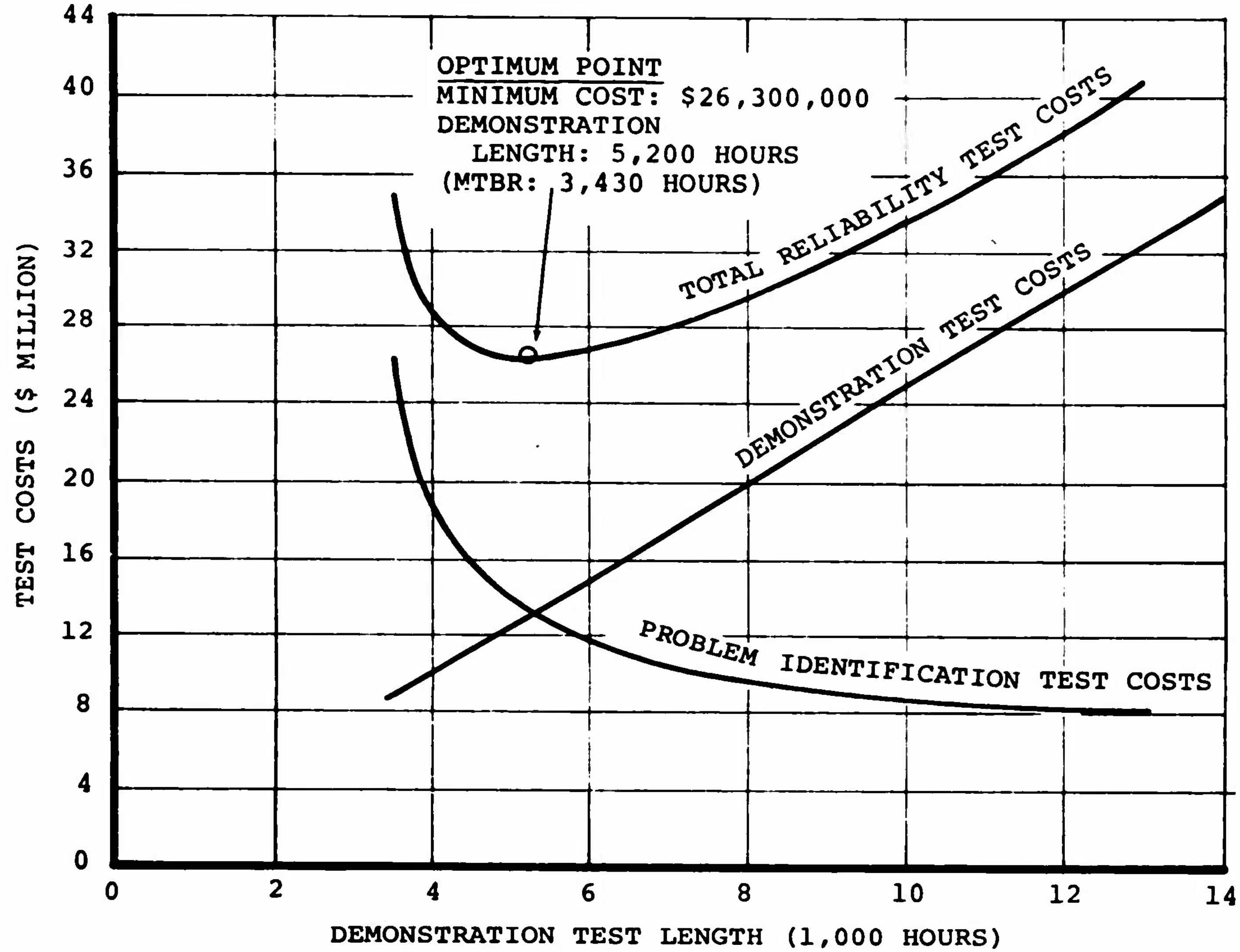

Figure 160. Total Reliability Test Costs Trade-Off Study for 1,000-Hour MTBR* at 90% Confidence, 80% Probability of Passing Demonstration, and 7-Year Demo-In.

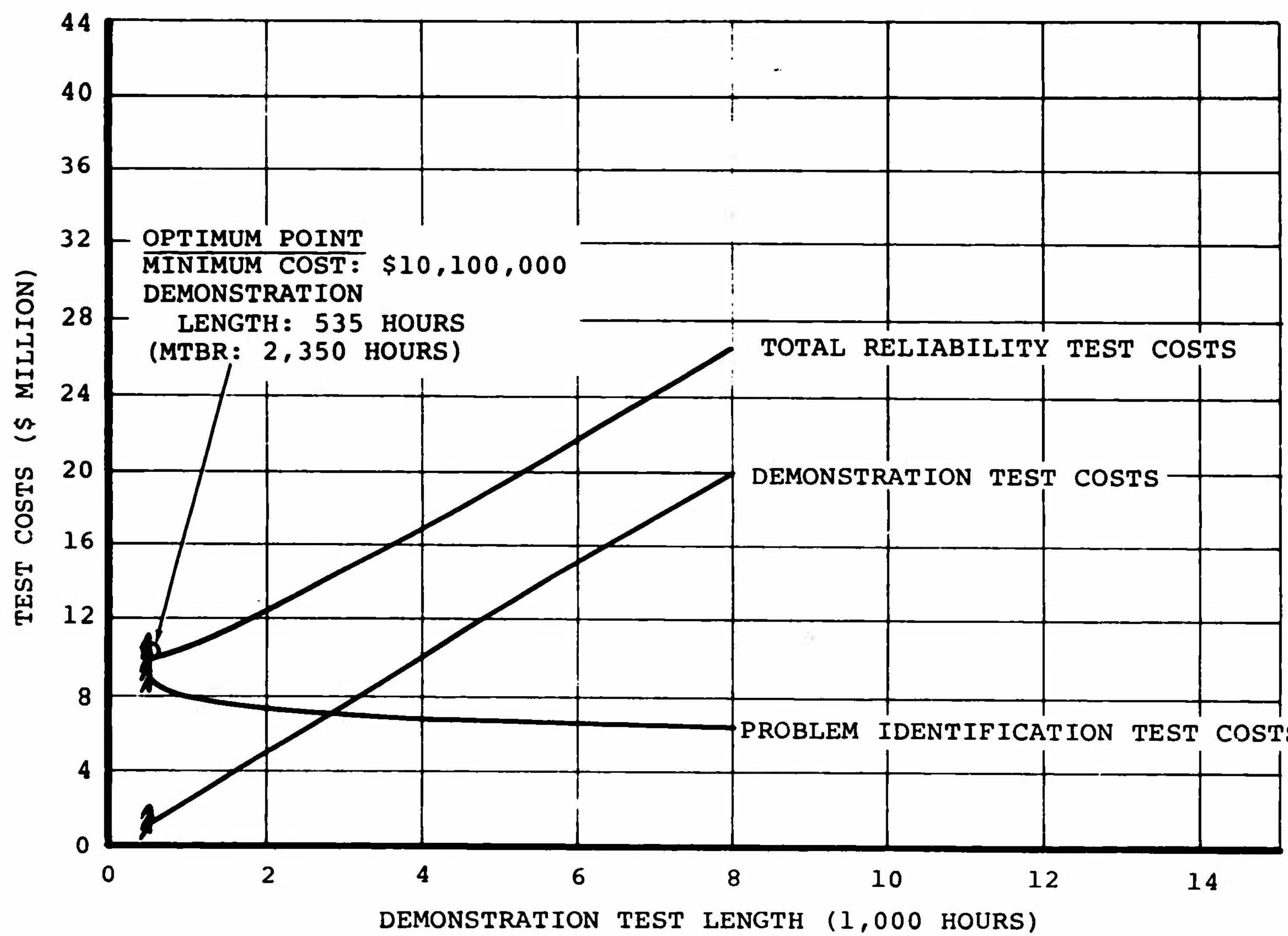

Figure 161. Total Reliability Test Costs Trade-Off Study for 1,500-Hour MTBR* at 30% Confidence, 80% Probability of Passing Demonstration, and 7-Year Demo-In.

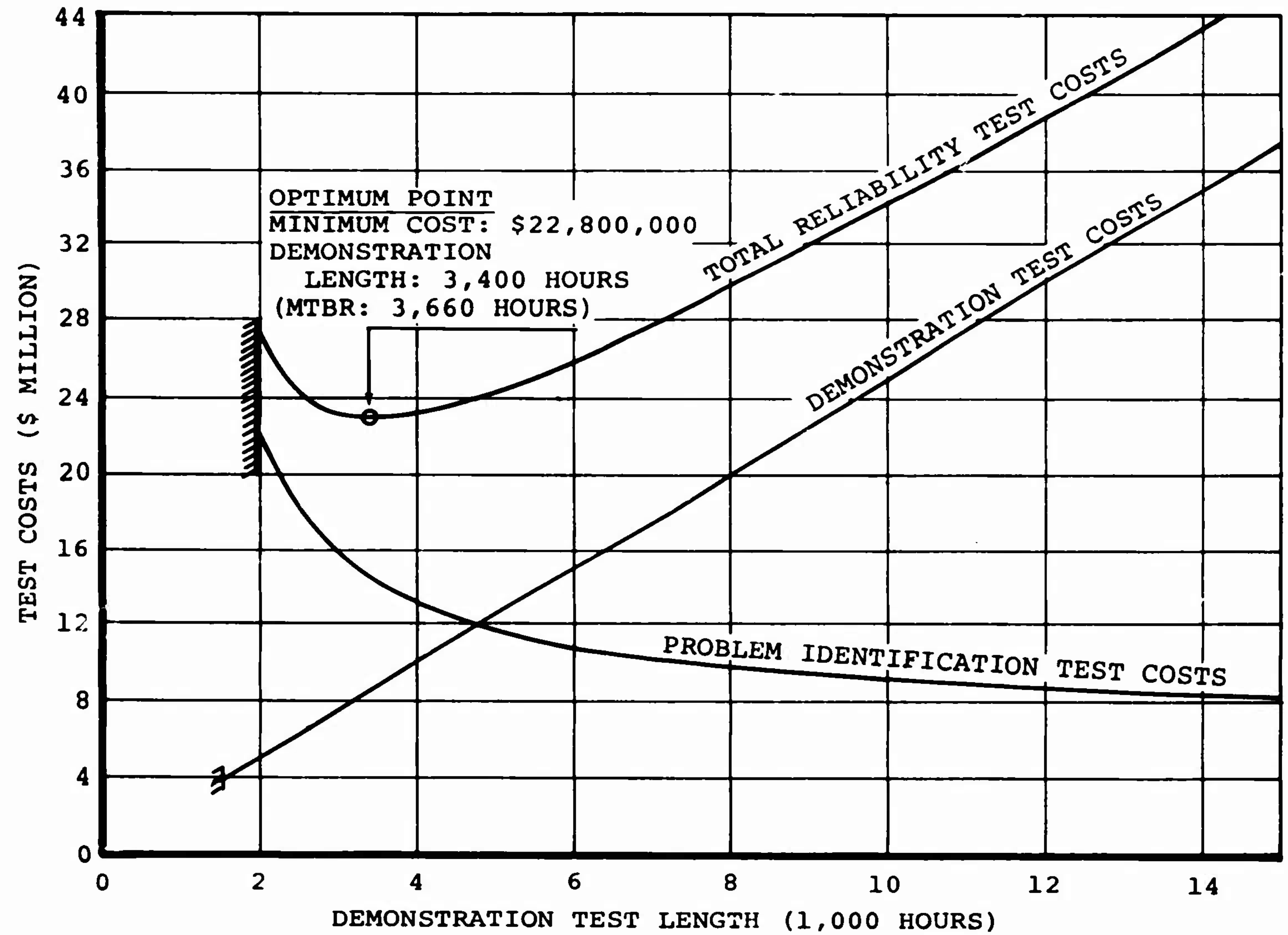

Figure 162. Total Reliability Test Costs Trade-Off Study for 1,500-Hour MTBR* at 60% Confidence, 80% Probability of Passing Demonstration, and 7-Year Demo-In.

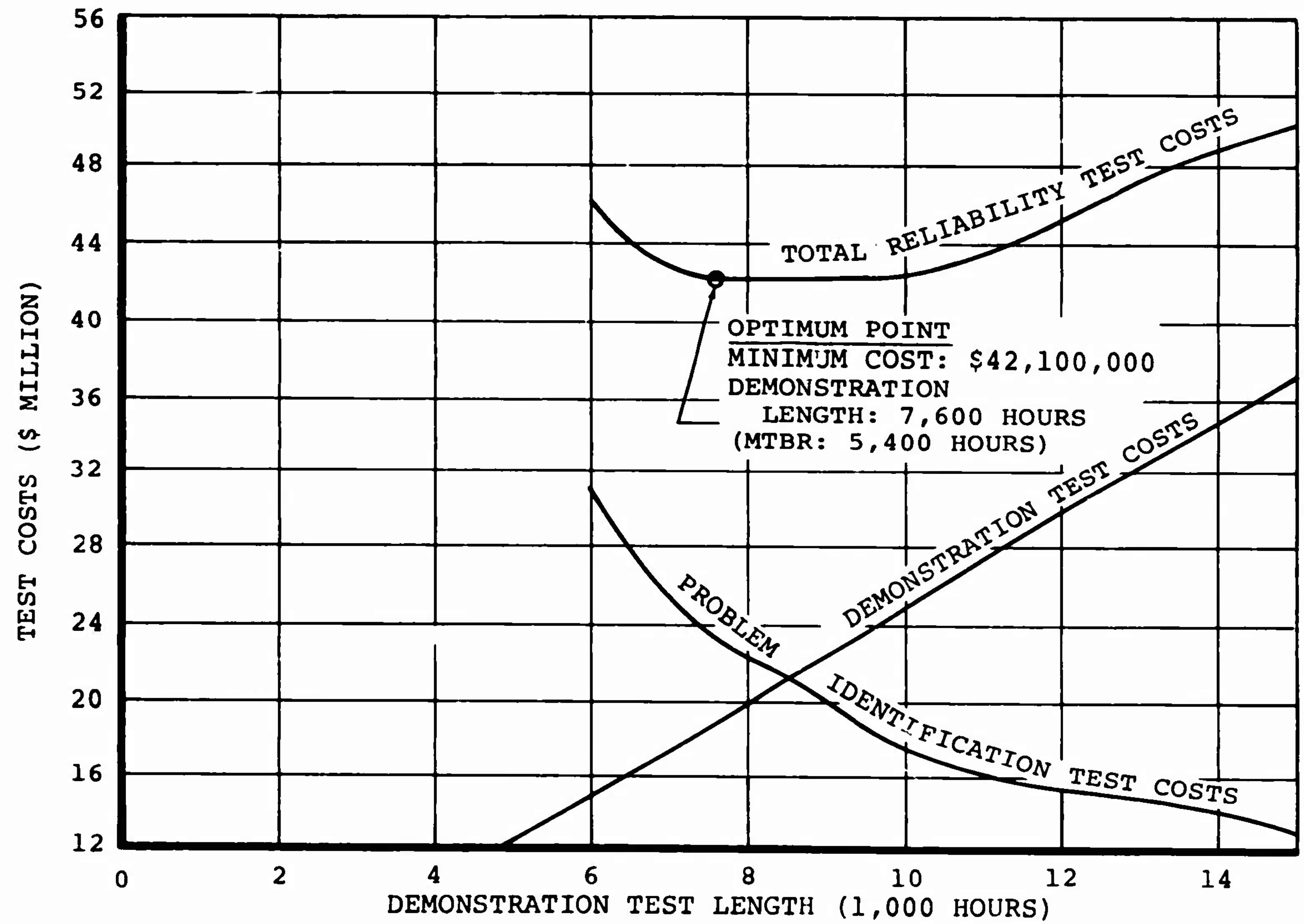

Figure 163. Total Reliability Test Costs Trade-Off Study for 1,500-Hour MTBR* at 90% Confidence, 80% Probability of Passing Demonstration, and 7-Year Demo-In.

APPENDIX VI
GENERAL DESCRIPTION OF TEST SETUPS

TYPE I TESTS

Fatigue Tests

Fatigue tests may be classified into two groups, reflecting setup configuration. The first group is characterized by use of a minimal holding fixture mounted on a commercial universal fatigue machine. A single force output of the machine supplies the load to the specimen. Traditionally, universal fatigue machines have the output force generated by a rotating unbalanced mass driven by a fixed speed motor; however, recent trends have been toward hydraulic servo actuator machines. Typically, fatigue strength data are acquired for pitch links in tension, transmission mounting lugs, synch shaft torsion, and rotor shaft bending.

The second group of fatigue tests is characterized by use of specialized fixtures, completely unique to the component being tested. Commonly, the tests will have more than one input. (e.g., the tension-torsion loading of a blade retention strap). An example of a specialized fixture is the setup for fatigue testing rotor blade segments. It consists of a rectangular welded framework with a springbank to apply the simulated blade centrifugal force, and a hydraulic servo actuator to force the blade at its natural frequency as a pinned-pinned beam.

Static Load Tests

Static load tests are employed to define some static property of the component such as yield load, ultimate load, spring constant, section property (EI), and/or stress concentration. A static load is applied to the specimen by weights, spring scales, rams, or commercially available loading machines. Deflections are measured optically or with dial indicators or strain gages. Examples of static load tests are a planet carrier strain survey and rotor blade EI determination.

Miscellaneous Tests

The miscellaneous group consists of tests that address specific potential failure modes. An example is a gear resonance test wherein a gear is excited electromagnetically over a range of frequencies to determine the gear's natural frequencies, modes, and nodal points, and to avoid resonance and fatigue failures in the aircraft. Other examples are the pressure, flow, and temperature tests performed on transmission oil systems to evaluate these systems.

TYPE II TESTS

Rotor Controls Bench Endurance - Back-to-Back Rig

Two swashplate assemblies are mounted in a fixture with one assembly inverted. The rotating rings are connected by instrumented aircraft pitch links. The nonrotating ring of the upper swashplate is connected to the fixture with turnbuckles, and the nonrotating ring of the lower swashplate is attached in a similar manner to a guided loading plate. Hydraulic cylinders apply vertical thrust loading with equal cylinder pressures and moment loading with unequal pressures. The swashplates may be tilted with respect to the horizontal plane to generate velocity at the pitch link bearings as the swashplate is rotated. An electric motor-driven shaft supplies torque to the swashplate drive scissors.

Helicopter Tiedown Test

The tiedown setup consists of an aircraft that has been modified to allow the addition of structural restraints to prevent flight under conditions of applied power. The structural restraints are attached from the thrust deck(s) of the aircraft to concrete masses at ground level. The aircraft rests in a support cradle to maintain a constant position. Aircraft equipments not essential to the test, such as landing gear and troop seats, are deleted from the aircraft. Pilots in the cockpit control the blade pitch and RPM, and hence the loading of the dynamic system components.

Dynamic Systems

Dynamic system components, from the engine transmission to rotor blades, are mounted on a welded framework. The framework is secured to concrete masses to provide vertical restraint. Aircraft engines are used as the source of power. Fuel is supplied from a nearby subterranean tank farm. Blade pitch and the resulting RPM are controlled from within a support building. The setup is similar to a tiedown, but with structural steel beams functioning as the airframe. (An example of this test technique is illustrated in Reference 2.)

Whirl Tower

A rotor hub with blades and upper controls is mounted atop the tower structure. Power is supplied by a variable speed electric drive system. Blade pitch and RPM are controlled from within the building enclosing the drive system.

Hub Bearings (Blade Articulation Bearings)

The setup for the rotor hub bearings applies a static radial load with a hydraulic ram to simulate the centrifugal force from a rotor blade. Moment loads are similarly applied to simulate blade flap and/or chordwise moments. The bearing angular oscillations are generated either by eccentric crank mechanisms or electrohydraulic servoactuators.

Transmission Closed Loop

The distinguishing characteristic of a closed loop transmission test setup is the interconnection of the test specimen's input and output shafts by additional shafting and transmissions, forming a continuous power loop. Static torque is applied to the loop by a differential gearbox located in the loop. An external, variable-speed electric motor drives the loop at the required RPM, supplying only power to accelerate the rotating members to the required speed, and to overcome frictional losses under steady state conditions. The lift, drag and pitching moment rotor loads are applied to appropriate transmissions by hydraulic rams. A rigid structural steel framework supports both the specimen and fixture transmissions.

Transmission Open Loop

Power in an open loop system flows from a high-power variable-speed electrical drive system, through commercial gearbox(es), through the test transmission(s) and is finally absorbed by a dynamometer or brake. The appropriate rotor loads and upper control loads are applied by hydraulic rams. A rigid structural frame supports the electric drive and commercial gearbox(es). Aircraft mounting structure may be used to adapt the transmission test specimens to the frame.

Tail Rotor Whirl Stand

The configuration of Helicopter "A" requires that a specific test technique be considered for the purpose of testing the antitorque (tail) rotor and its drive system. The aircraft components mounted on the stand include the drive and rotor components from the intermediate transmission to the tail rotor blades. The aircraft components are supported in a structural steel framework. Power is transmitted from a variable-speed electric drive and commercial gearbox to the input shaft of the intermediate transmission. The rotor pitch and RPM are controlled from a support building.